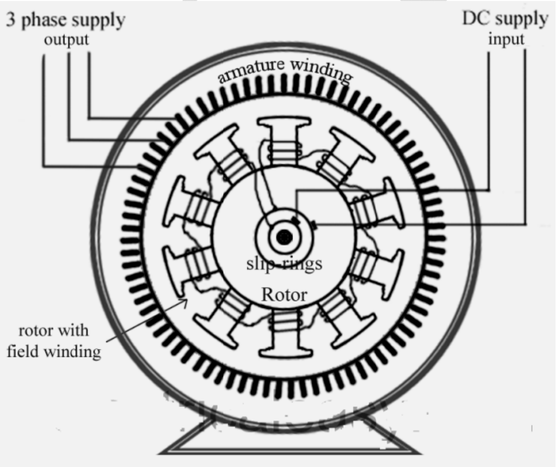
UNIT I SYNCHRONOUS GENERATOR

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

Constructional Details

AC generators or alternators operate on the principle of electromagnetic induction.
The construction consists of armature winding mounted on a stationary element called **stator** and field windings on a rotating element called rotor.



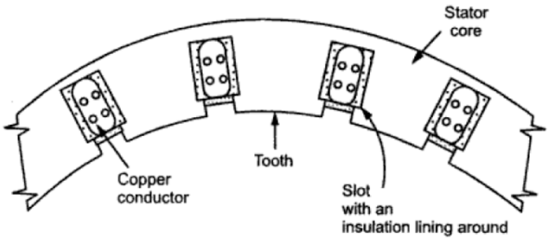
- The stator consists of a cast-iron frame, which supports the armature core, having slots on its inner periphery for housing the armature conductors.
- The rotor is like a flywheel having alternate *N* and *S* poles fixed to its outer rim.
- The magnetic poles are excited (or magnetized) from direct current supplied by a d.c. source at 125 to 600 volts.
- Because the field magnets are rotating, this current is supplied through two slip rings.
- As the exciting voltage is relatively small, the slip-rings and brush gear are of light construction.
- When the rotor rotates, the stator conductors (being stationary) are cut by the magnetic flux, hence they have induced e.m.f. produced in them.
- Because the magnetic poles are alternately *N* and *S*, they induce an e.m.f. and hence current in armature conductors, which first flows in one direction and then in the other.
- Hence, an alternating e.m.f. is produced in the stator conductors **(*i*)** whose frequency depends on the number of *N* and *S* poles moving past a conductor in one second and **(*ii*)** whose direction is given by Fleming's Right-hand rule.

Advantages of having stationary armature (and a rotating field system) are:

1. The output current can be led directly from fixed terminals on the stator (or armature windings) to the load circuit, without having to pass it through brush-contacts.
2. It is easier to insulate stationary armature winding for high a.c. voltages, which may have as high a value as 30 kV or more.
3. The sliding contacts *i.e.* slip-rings are transferred to the low-voltage, low-power d.c. field circuit which can, therefore, be easily insulated.
4. The armature windings can be more easily braced to prevent any deformation, which could be produced by the mechanical stresses set up as a result of short-circuit current and the high centrifugal forces brought into play.

Stator

(i) Stator Frame

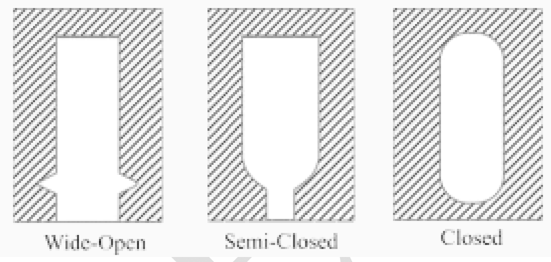


- It is used for holding the armature stampings and windings in position.
- Ventilation is maintained with the help of holes cast in the frame itself.
- The provision of radial ventilating spaces in the stampings assists in cooling the machine.

(ii) Stator core

- The armature core is supported by stator frame and is made up of laminations of special magnetic iron or steel alloy.

- The core is laminated to minimize loss due to eddy currents.
- The laminations are stamped out in complete rings (for smaller machine) or in segments (for larger machines).
- The laminations are insulated from each other and have spaces between them for allowing the cooling air to pass through.
- The slots for housing the armature conductors lie along the inner periphery of the core and are stamped out at the same time when laminations are formed.

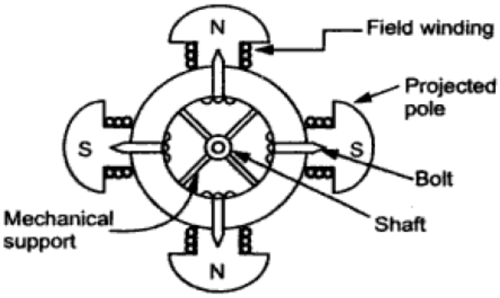


- Different shapes of the armature slots are shown in Fig.
- The wide-open type slot has the advantage of permitting easy installation of form-wound coils and their easy removal incase of repair. But it has the disadvantage of distributing the air-gap flux into bunches or tufts, that produce ripples in the wave of the generated e.m.f.
- The semi-closed type slots are better in this respect, but do not allow the use of form-wound coils.
- The wholly-closed type slots or tunnels do not disturb the air-gap flux but ***(i)*** they tend to increase the inductance of the windings ***(ii)*** the armature conductors have to be threaded through, thereby increasing initial labour and cost of winding and ***(iii)*** they present a complicated problem of end connections. Hence, they are rarely used.

Rotor

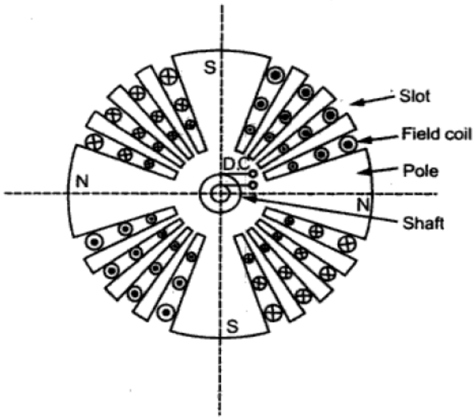
Two types of rotors are used in alternators ***(i)*** salient-pole type and ***(ii)*** smooth-cylindrical type.

(i) **Salient (or projecting) Pole Type**



- It is used in low-and medium-speed (engine driven) alternators.
- It has a large number of projecting (salient) poles, having their cores bolted or dovetailed onto a heavy magnetic wheel of cast-iron, or steel of good magnetic quality.
- Such generators are characterized by their large diameters and short axial lengths.
- The poles and pole-shoes are laminated to minimize heating due to eddy currents.

(ii) Smooth Cylindrical Type Rotor



- Smooth Cylindrical Type Rotor is also called non-salient type or non-projected pole type or round rotor construction.
- The rotor consists of smooth solid steel cylinder, having number of slots to accommodate the field coil.
- The slots are covered at the top with the help of steel or manganese wedges.
- The un-slotted portions of the cylinder itself act as the poles.
- The poles are not projecting out and the surface of the rotor is smooth which maintains uniform air gap between stator and the rotor.
- These rotors have small diameters and large axial lengths. This is to keep peripheral speed within limits.
- The main advantage of this type is that these are mechanically very strong and thus preferred for high speed alternators ranging between 1500 to 3000r.p.m.
- Such high speed alternators are called **'turbo-alternators'**.
- The prime movers used to drive such type of rotors are generally steam turbines, electric motors.
- The cylindrical rotor alternators are generally designed for 2-pole type giving very high speed of $N_s = (120 \times f)/P = (120 \times 50) / 2 = 3000$ rpm.

Frequency of Induced E.M.F.

P = Number of poles
N = Speed of the rotor in r.p.m.
and f = Frequency of the induced e.m.f.

One mechanical revolution of rotor = P/2 cycles of e.m.f. electrically

Thus there are P/2 cycles per revolution.

As speed is N r.p.m., in one second, rotor will complete (N/60) revolutions.

But cycles/sec. = Frequency = f

∴ Frequency f = (No. of cycles per revolution) x (No. of revolutions per second)

f = (P/2) x (N/60) = (PN/120) Hz (cycles per sec).

So there exists a fixed relationship between three quantities, the number of poles P. the speed of the rotor N in r.p.m. and f the frequency of an induced em.f. in Hz (Hertz).

Synchronous Speed $N_s = 120f/P$ rpm

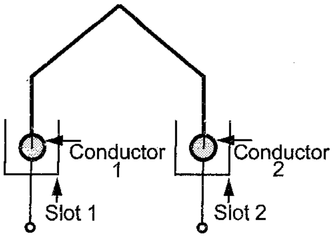
Winding Terminologies

(i) Conductor: The part of the wire, which is under the influence of the magnetic field and responsible for the induced e.m.f. is called active length of the conductor. The conductors are placed in the armature slots.

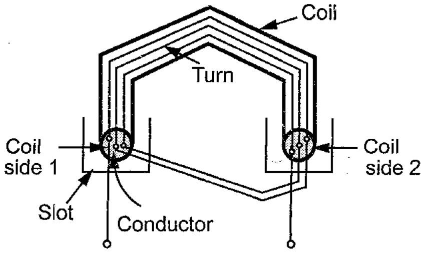
(ii) Turn: A conductor in one slot, when connected to a conductor in another slot forms a turn. So two conductors constitute a turn.

(iii) Coil: As there are number of turns, for simplicity the number of turns are grouped together to form a coil. Such a coil is called multiturn coil. A coil may consist of single turn called single turn coil.

(iv) Coil Side: Coil consists of many turns. Part of the coil in each slot is called coil side of a coil as shown in the Fig.



(a) Turn



(b) Multiturn coil

(v) Pole Pitch (n): It is center to center distance between the two adjacent poles.

Pole pitch = 180° electrical
= slots per pole (number of slots / P) = n

(vi) Slot Angle (β) : The phase difference contributed by one slot in degrees electrical is called slot angle β.

As slots per pole contributes 180° electrical which is denoted as n,

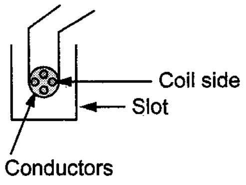
$$1 \text{ slot angle} = \frac{180^0}{n} \quad \text{or } \beta = \frac{180^0}{n}$$

Types of Armature Windings

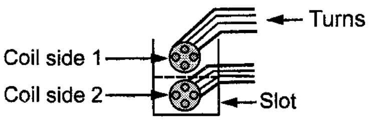
i) Single layer and double layer winding
ii) Full pitch and short pitch winding
iii) Concentrated and distributed winding.

(i) Single Layer and Double Layer Winding

If a slot consists of only one coil side, winding is said to be single layer. While there are two coil sides per slot, one at the bottom and one at the top the winding is called double layer as shown in the Fig. A lot of space gets wasted in single layer hence in practice generally double layer winding is preferred.



(a) Single layer

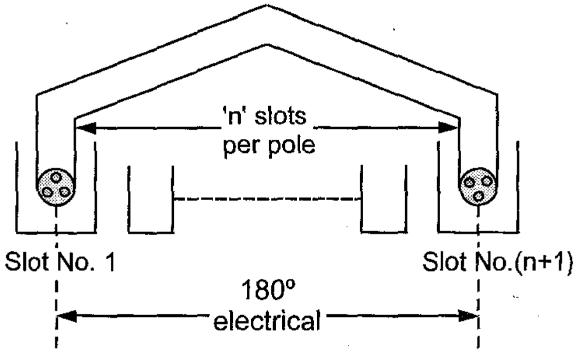


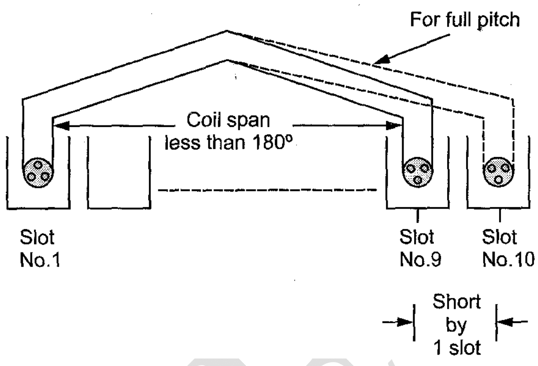
(b) Double layer

(ii) Full Pitch and Short Pitch Winding

If coil side in one slot is connected to a coil side in another slot which is one pole pitch distance way from first slot, the winding is said to be full pitch winding.

Coil span It is the distance on the periphery of the armature between two coil sides of a coil. It is usually expressed in terms of number of slots or degrees electrical. So if coil span is n slots or 180° electrical the coil is called full pitch coil. This is shown in the Fig.





If coil span is slightly less than a pole pitch i.e. less than 180^0 electrical, the coils are called, short pitched coils or fractional pitched coils. Generally coils are shorted by one or two slots.

Advantages of Short Pitch Coils

a) The length required for the end connections of coils is less i.e. inactive length a winding is less. So less copper is required. Hence economical.

b) Short pitching eliminates high frequency harmonics which distort the sinusoidal nature of e.m.f. Hence waveform of an induced e.m.f. is more sinusoidal due to short pitching.

c) As high frequency harmonics get eliminated, eddy current and hysteresis losses which depend on frequency also get minimised. This increases the efficiency.

(iii) Concentrated and Distributed Winding

If all conductors or coils belonging to a phase are placed in one slot under every pole, it is concentrated winding.

If 'x' conductors per phase are distributed among the available slots per phase under every pole, the winding is called distributed winding.

Winding Factors

Winding Factor (K_w) is defined as the product of Distribution factor (K_d) and the coil span factor (K_c).

Pitch factor or Chording factor or Coil span factor:

The factor by which, induced emf gets reduced due to short pitching is called pitch factor or coil span factor denoted by K_c.

Pitch factor or coil span factor K_p or K_c is defined as

$$= \frac{\text{vector sum of the induced emfs per coil}}{\text{arithmetic sum of the induced emfs per coil}}$$

$$= \frac{\text{resultant emf when coil is short pitched}}{\text{resultant emf when coil is full pitched}}$$

∴ $K_c = \cos(\alpha/2)$ where α = angle of short pitch (the angle by which coils are short pitched)

$\alpha = 180^0$ – actual coil span of the coils.

Distribution factor or Breadth factor or Winding factor or Spread factor (K_d)

The factor by which there is a reduction in the emf due to distribution of coils is called distribution factor K_d.

$$K_d = \frac{\text{emf with distributed winding}}{\text{emf with concentrated winding}}$$

$$= \frac{\sin m\beta/2}{m \sin \beta/2}$$

Where m = slots/pole/phase

β = slot angle = $180^0/n$

n = slots/ pole

Equation of Induced E.M.F.

Let Z = No. of conductors or coil sides in series/phase

= 2T — where *T* is the No. of coils or turns per phase

P = No. of poles

f = frequency of induced e.m.f. in Hz

Φ = flux/pole in webers

K_d = distribution factor = $\frac{\sin m\beta/2}{m \sin \beta/2}$

K_c or K_p = pitch factor or coil span factor = $\cos(\alpha/2)$

K_f = form factor = 1.11

N = rotor rpm

In one revolution of the rotor (i.e. in 60/N second) each stator conductor is cut by a flux of ΦP webers.

$\therefore \quad d\Phi = \Phi P \text{ and } dt = 60/N$

$\therefore$ Average emf induced per conductor $= \frac{d\Phi}{dt} = \frac{\Phi P}{60/N} = \frac{\Phi NP}{60}$

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

$\therefore \quad$ Average emf per conductor $= \frac{\Phi P}{60} \times \frac{120\,f}{P} = 2\,f\,\Phi$ volt

If there are Z conductors in series/phase, then average emf/phase = 2fΦZ volt = 4fΦT volt

RMS value of emf/phase = 1.11 x 4fΦT = 4.44 fΦT

Actual available voltage/phase = $4.44\, K_c\, K_d\, f\Phi T$ volt.

= $4\, K_c\, K_d\, K_f\, f\Phi T$ volt.

If alternator is star connected, then line voltage is $\sqrt{3}$ times the phase voltage.

Effect of Harmonics on Pitch and Distribution Factors

(a) If the short-pitch angle or chording angle is α degrees (electrical) for the fundamental flux wave, then its values for different harmonics are

pitch-factor, k_c = $\cos \alpha/2$ —for fundamental

= $\cos 3\alpha/2$ —for 3rd harmonic

= $\cos 5\alpha/2$ —for 5th harmonic etc.

(b) Similarly, the distribution factor is also different for different harmonics. Its value becomes

$$Kd = \frac{\sin m\beta/2}{m \sin \beta/2}$$

where *n* is the order of the harmonic

for fundamental, $n = 1$ $\quad kd1 = \frac{\sin m\beta/2}{m \sin \beta/2}$

for 3rd harmonic, $n = 3$ $\quad kd3 = \frac{\sin 3\, m\beta/2}{m \sin 3\beta/2}$

for 5th harmonic, $n = 5$ $\quad kd5 = \frac{\sin 5\, m\beta/2}{m \sin 5\beta/2}$

(c) If fundamental frequency is 50 Hz. Then for 3^{rd} harmonic $f_3 = 3 \times 50 = 150$ Hz, for 5^{th} harmonic, $f_5 = 5 \times 50 = 250$ Hz.etc.

Alternator on Load

As the load on an alternator is varied, its terminal voltage is also found to vary as in d.c. generators.

This variation in terminal voltage *V* is due to the following reasons:

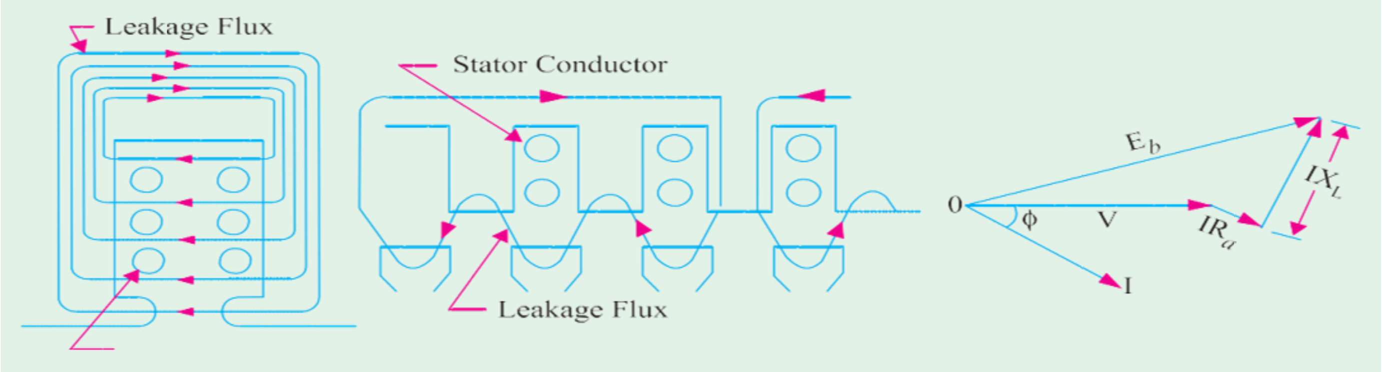
- voltage drop due to armature resistance R_a
- voltage drop due to armature leakage reactance X_L
- voltage drop due to armature reaction

Armature Resistance

The armature resistance/phase R causes a voltage drop/phase of IR_a which is in phase with the armature current I. However, this voltage drop is practically negligible.

Armature Leakage Reactance

- When current flows through the armature conductors, fluxes are set up which do not cross the air-gap, but take different paths. Such fluxes are known as *leakage fluxes*. Various types of leakage fluxes are shown in Fig.



- The leakage flux is practically independent of saturation, but is dependent on I and its phase angle with terminal voltage V.
- This leakage flux sets up an e.m.f. of self-inductance which is known as *reactance e.m.f.* and which is ahead of I by 90°.
- Hence, armature winding is assumed to possess leakage reactance X_L (also known as Potier rectance X_P) such that voltage drop due to this equals IX_L.
- A part of the generated e.m.f. is used up in overcoming this reactance e.m.f.

$$\boldsymbol{E = V + I\,(R + jX_L)}$$

Armature Reaction

- There are two fluxes present in the air gap,
  - Due to armature current
  - Due to current in field (main) winding
- Armature reaction is the effect of armature flux on the main field flux.
- The effect of armature flux not only depends on the magnitude of the current flowing through the armature winding but also depends on the nature of the power factor of the load connected to the alternator.

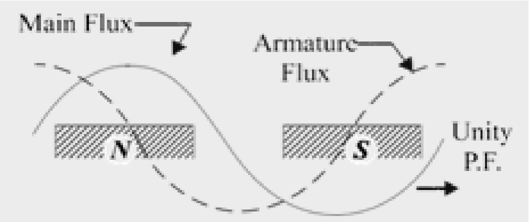
Consider three cases:

(i) When load of p.f. is unity

(ii) when p.f. is zero lagging and

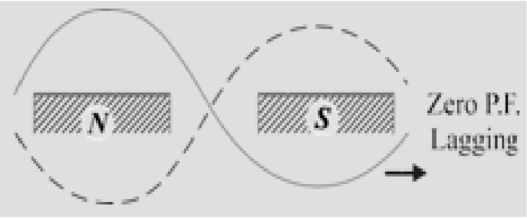
(iii) When p.f. is zero leading.

Unity Power Factor



- In this case the armature flux is cross-magnetizing.
- The result is that the flux at the leading tips of the poles is reduced while it is increased at the trailing tips.
- However, these two effects nearly offset each other leaving the average field strength constant.
- Armature reaction for unity p.f. is distortional.

Zero P.F. lagging



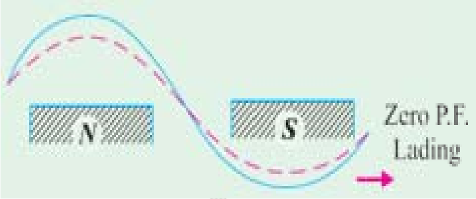
- the armature flux (whose wave has moved backward by 90°) is in direct opposition to the main flux.
- Hence, the main flux is decreased. Therefore, it is found that armature reaction, in this case, is wholly ***demagnetizing***, with the result, that due to weakening of the main flux, less e.m.f. is generated.

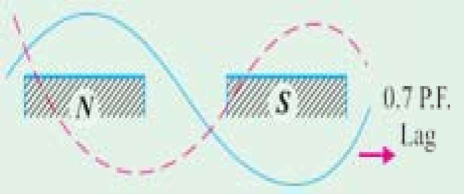
- To keep the value of generated e.m.f. the same, field excitation will have to be increased to compensate for this weakening.

Zero P.F. leading

- armature flux wave has moved forward by 90° so that it is in phase with the main flux wave. This results in added main flux. Hence, in this case, armature reaction is wholly *magnetising*, which results in greater induced e.m.f.
- To keep the value of generated e.m.f. the same, field excitation will have to be reduced somewhat.

- For intermediate power factor, the effect is partly distortional and partly demagnetising (because p.f. is lagging).





Synchronous Reactance

- For the same field excitation, terminal voltage is decreased from its no-load value E_0 to V (for a lagging power factor). This is because of
  - drop due to armature resistance, IR_a
  - drop due to leakage reactance, IX_L
  - Drop due to armature reaction.
- The drop in voltage due to armature reaction may be accounted for by assuming the presence of a fictitious reactance X_a in the armature winding. The value of X_a is such that IX_a represents the voltage drop due to armature reaction.
- The leakage reactance X_L and the armature reactance X_a may be combined to give synchronous reactance X_S.

  Hence $X_S = X_L + X_a$
- Therefore, total voltage drop in an alternator under load is

  $= IR_a + jIX_S = I(R_a + jX_S) = IZ_S$

  where Z_S is known as synchronous impedance of the armature,
- Hence, the vector difference between no-load voltage E_0 and terminal voltage V is equal to IZ_S.

Voltage Equation of an Alternator

$E_{ph} = V_{ph} + I_aR_a + I_aX_s$

Phasor or Vector Diagram of a Loaded Alternator

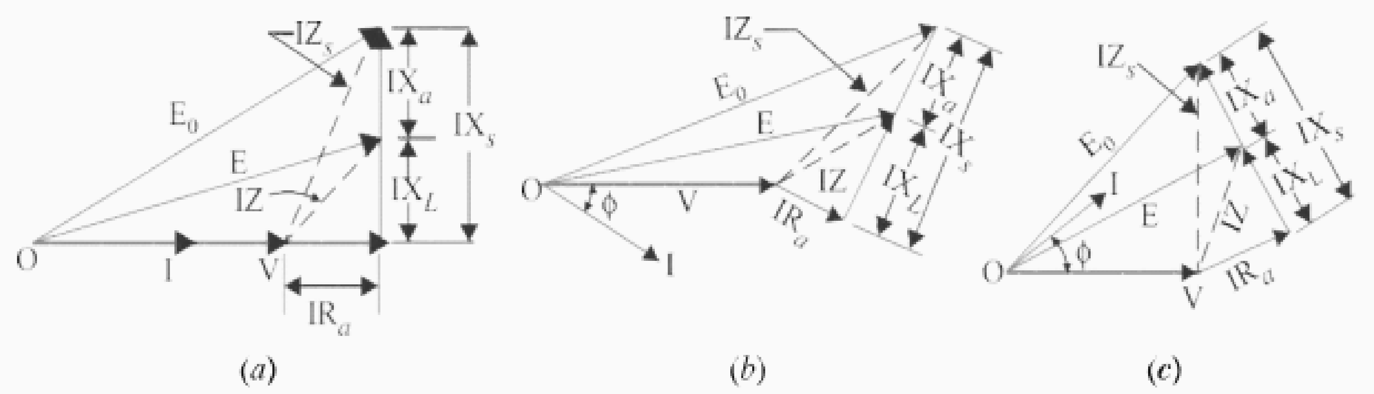
E_0 or Eph = No load emf - Voltage induced in armature in the absence of all voltage drops. Hence it represents the maximum value of the induced emf.

E = load induced emf – it is the induced emf after allowing for armature reaction. E is vectorially less than E_{ph} by I_aX_a.

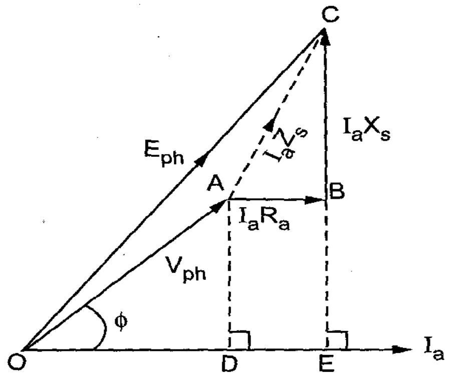
V_{ph} = terminal voltage – it is vectorially less than E_{ph} by I_aZ_s.

Where $Z_s = \sqrt{R_a^2 - X_s^2}$

I or I_a = armature current / phase and Φ = load p.f angle.



(a) Unity p.f. (b) Lagging p.f (c) leading p.f.



To find the value of induced emf.

Lagging power factor load.

The vector diagram can be redrawn and the value of induced emf can be found.

From vector diagram, $OD = V_{ph}\cos\Phi$

$AD = BE = V_{ph}\sin\Phi$

$DE = I_aR_a$

From Δ OCE, $OC^2 = OE^2 + EC^2$

$\therefore \quad E_{ph}^2 = (OD + DE)^2 + (EB + BC)^2$

$E_{pf}^2 = (Vph\cos\varphi + IaRa)^2 + (Vph\sin\varphi + IaXs)^2$

$E_{ph} = \sqrt{(Vph\cos\varphi + IaRa)^2 + (Vph\sin\varphi + IaXs)^2}$

Where,

V_{ph} – phase value of rated voltage

I_a – phase value of current

Cos φ – p.f. of load

Similarly, the equation can be derived for other power factors.

In general,

No load induced e.m.f per phase,

$$E_{ph} = \sqrt{(Vph\cos\varphi + IaRa)^2 + (Vph\sin\varphi \pm IaXs)^2}$$

Where,

V_{ph} – phase value of rated voltage

I_a – phase value of current

Cos φ – p.f. of load

+ ve sign for lagging power factor

-ve sign for leading power factor

Voltage Regulation of an Alternator

The voltage regulation of an alternator is defined as the change in its terminal voltage when full load is removed, keeping field excitation and speed constant, divided by the rated terminal voltage.

So if V_{ph} = Rated terminal voltage and E_{ph} = No load induced e.m.f.

then voltage regulation is defined as,

$$\boxed{\%\ \text{Regulation} = \frac{E_{ph} - V_{ph}}{V_{ph}} \times 100}$$

Methods of Determining the Regulation

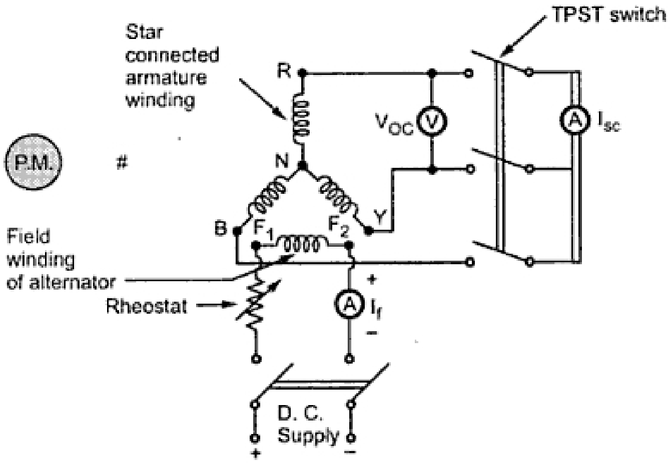
A. **Synchronous Impedance Method or E.M.F. Method**

The method requires following data to calculate the regulation.

1. The armature resistance per phase (R_a).
2. **Open circuit characteristics -** which is the graph of open circuit voltage against the field current. This is possible by conducting open circuit test on the alternator.
3. **Short circuit characteristics -** which is the graph of short circuit current against field current. This is possible by conducting short circuit test on the alternator.

The alternator is coupled to a prime mover capable of driving the alternator at its synchronous speed. The armature is connected to the terminals of a switch. The other terminals of the switch are short circuited through an ammeter. The voltmeter is connected across the lines to measure the open circuit voltage of the alternator.

The field winding is connected to a suitable d.c. supply with rheostat connected in series. The field excitation i.e. field current can be varied with the help of this rheostat. The circuit diagram is shown in the Fig.



O.C. Test:

Procedure:

i) Start the prime mover and adjust the speed to the synchronous speed of the alternator.

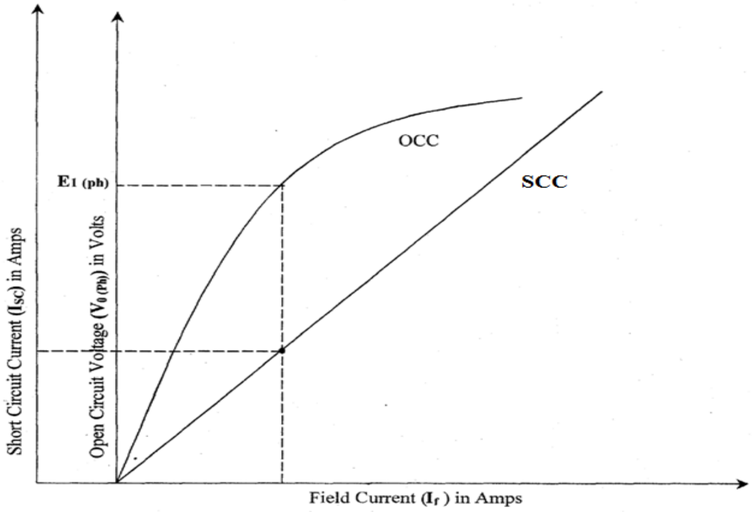
ii) Keeping rheostat in the field circuit maximum, switch on the d.c. supply.

iii) The T.P.S.T switch in the armature circuit is kept open.

iv) With the help of rheostat, field current is varied from its minimum value to the rated value. Due to this, flux increases, increasing the induced e.m.f. Hence voltmeter reading, which is measuring line value of open circuit voltage increases. For various values of field current, voltmeter readings are observed. Graph of $(V_{oc})_{ph}$ against I_f is plotted.

S.C.Test

After completing the open circuit test observation, the field rheostat is brought to maximum position, reducing field current to a minimum value. The T.P.S.T switch is closed. As ammeter has negligible resistance, the armature gets short circuited. Then the field excitation is gradually increased till full load current is obtained through armature winding. This can be observed on the ammeter connected in the armature circuit. The graph of short circuit armature current against field current is plotted from the observation table of short circuit test. This graph is called short circuit characteristics, S.C.C.



- The S.C.C. is a **straight line** graph passing through the origin while O.C.C. resembles B-H curve of a magnetic material.

Determination of Impedance from O.C.C. and S.C.C.

The synchronous impedance of the alternator changes as load condition changes. O.C.C. and S.C.C. can be used to determine Z_s for any load and load p.f. conditions.

$$\text{Synchronous impedance, } Z_s = \frac{\text{open circuit voltage,E1(ph)}}{\text{short circuit current,Isc}} \text{ (from graph)}$$

4. Regulation Calculations:

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

The armature resistance per phase (R_a) 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.

$$\text{Synchronous reactance, } X_s = \sqrt{(Zs^2 - Ra^2)}\ \Omega/\text{ph}$$

So synchronous reactance per phase can be determined.

No load induced e.m.f per phase,

$$E_{ph} = \sqrt{(V_{ph}\cos\varphi + I_aR_a)^2 + (V_{ph}\sin\varphi \pm I_aX_s)^2}$$

Where,

V_{ph} – phase value of rated voltage, I_a – phase value of current, Cos φ – p.f. of load
+ ve sign for lagging power factor, -ve sign for leading power factor

$$\%\ \text{regulation} = \frac{(E_{ph} - V_{ph})}{V_{ph}} \times 100$$

5.Advantages and Limitations of Synchronous Impedance Method:

Advantage:

Synchronous impedance Z_s for any load condition can be calculated. Hence regulation of the alternator at any load condition and load power factor can be determined.

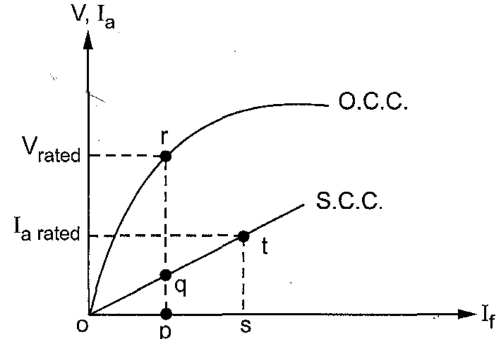
Limitation:

The main limitation of this method is that the method gives large values of synchronous reactance. This leads to high values of percentage regulation than the actual results. Hence this method is called **pessimistic method.**

Short Circuit Ratio and Its Significance

The short circuit ratio is the ratio of the excitation required to produce open circuit voltage equal to the rated voltage to the excitation required to produce rated full load current under short circuit.

$$\text{SCR (short circuit ratio)} = \frac{I_f \text{ for rated open circuit voltage}}{I_f \text{ for rated short circuit current}}$$



$$\text{From open and short circuit test, } Z_s = \frac{V_{oc\,(ph)}}{I_{asc(ph)}} \text{ for same } I_f$$

$$= X_s \text{ (neglecting } R_a)$$

$$\text{The per unit value of } X_s \text{ is, } X_{s\,(pu)} = \frac{X_s}{\text{Base impedance}}$$

$$\text{Base impedance} = \frac{\text{rated voltage per phase}}{\text{rated armature current per phase}}$$

$$\text{From fig. base impedance} = \frac{V_{rated}}{I_{a\,rated}} = \frac{pr}{st}$$

$$\text{But } X_s = \frac{pr}{pq} \text{ at same } I_f = op$$

$$\therefore X_{s\,(pu)} = \frac{\frac{pr}{pq}}{\frac{pr}{st}} = \frac{st}{pq}$$

$$\text{But SCR} = \frac{I_f \text{ for rated open circuit voltage}}{I_f \text{ for rated short circuit current}} = \frac{op}{os}$$

$$\text{Triangle opq and ost are similar, hence } \frac{op}{os} = \frac{pq}{st}$$

$$\therefore X_{s\,(pu)} = \frac{1}{\frac{pq}{st}} = \frac{1}{SCR}$$

Significance of SCR

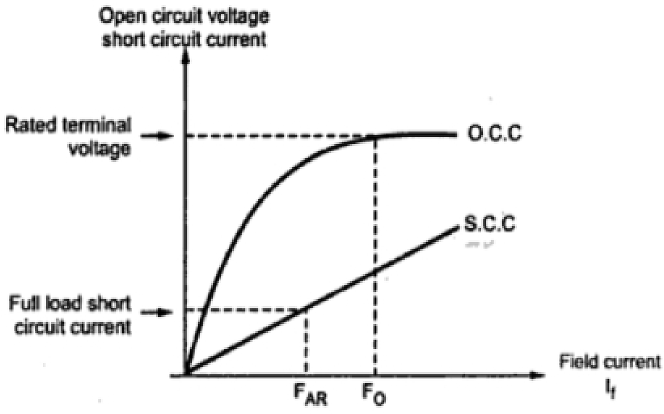
- For low value of.SCR, the value of Xs is more hence the drop IaXs is more. Hence the machine requires large changes in the field current (excitation) for the small changes in the load, to keep terminal voltage constant.
- A low value of SCR indicates smaller air gap and poor regulation due to large IaXs drop.
- The synchronous power is inversely proportional to Xs. This is the power which keeps alternators in synchronism during parallel operation and maintains the stability. Any disturbances from equilibrium conditions are compensated by synchronizing power. For low value of SCR, X is very large and synchronizing power is very low.

As synchronizing power decreases, tendency of alternators to remain in synchronism decreases. This decreases the stability. Thus low SCR puts the stability limit.

- The SCR can be increased by increasing the air gap but this needs more mmf to obtain same emf . Hence the pole size increases which increases the overall size and cost of the machine.
- Practically the SCR value is selected between 0.5 to 1.2.

B. Rothert's MMF or Ampere turn Method or MMF method

- The method is based on the results of open circuit test and short circuit test on an alternator.
- For any synchronous generator i.e. alternator, it requires m.m.f. which is product of field current and turns of field winding for two separate purposes.
  1. It must have an m.m.f. necessary to induce the rated terminal voltage on open circuit.
  2. It must have an m.m.f. equal and opposite to that of armature reaction m.m.f.
- The field m.m.f. required to induce the rated terminal voltage on open circuit can be obtained from open circuit test results and open circuit characteristics. This is denoted as F_O.
- The synchronous impedance has two components, armature resistance and synchronous reactance.
- Synchronous reactance also has two components, armature leakage reactance and armature reaction reactance.
- In short circuit test, field m.m.f. is necessary to overcome drop across armature resistance and leakage reactance and also to overcome effect of armature reaction.
- But drop across armature resistance and leakage reactance is very small and can be neglected.
- Thus in short circuit test, field m.m.f. circulates the full load current balancing the armature reaction effect.
- The value of ampere-turns required to circulate full load current can be obtained from short circuit characteristics. This is denoted as F_{AR}.
- The armature reaction reactance is dominating and hence the power factor of such purely reactive circuit is zero lagging. Hence F_{AR} gives demagnetizing ampere turns.
- The two components of total field m.m.f. which are F_O and F_{AR} are indicated in O.C.C. (open circuit characteristics) and S.C.C. (short circuit characteristics) as shown in the Fig.



- If the alternator is supplying full load, then total field m.m.f. is the vector sum of its two components F_O and F_{AR}.
- This depends on the power factor of the load which alternator is supplying.
- The resultant field m.m.f. is denoted as F_R.

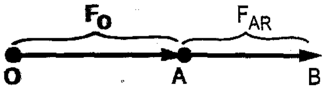
Zero lagging p.f. : As long as power factor is zero lagging, the armature reaction is completely demagnetising. Hence the resultant F_R is the algebraic sum of the two components F_O and F_{AR}. Field m.m.f. is not only required to produce rated terminal voltage but also required to overcome completely demagnetising armature reaction effect.

$OA = F_O$

$AB = F_{AR}$ demagnetizing

$OB = F_R = F_O + F_{AR}$

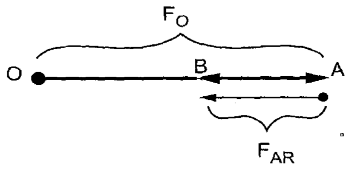
Total field m.m.f. is greater than F_O.



Zero leading p.f.: When the power factor is zero leading then the armature reaction is totally magnetising and helps main flux to induce rated terminal voltage. Hence net field m.m.f. required is less than that required to induce rated voltage normally, as part of its function is done by magnetising armature reaction component. The net field m.m.f. is the algebraic difference between the two components F_O and F_{AR}.

$OA = F_O$

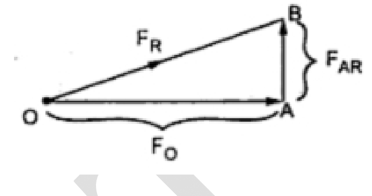
$AB = F_{AR}$ magnetizing



$OB = F_O - F_{AR} = F_R$
Total m.m.f. is less than F_O

Unity p.f. : Under unity power factor condition, the armature reaction is cross magnetising and its effect is to distort the main flux. Thus and F are at right angles to each other and hence resultant m.m.f. is the vector sum of F_O and F_{AR}.

$OA = F_O$
$AB = F_{AR}$ cross magnetising
$OB = F_R = F_0 + F_{AR}$ (adding vectorially)

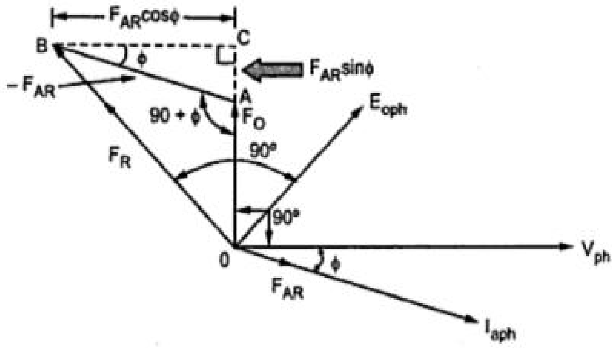


General Case:

The resultant m.m.f. is to be determined by vector addition of F_O and F_{AR}.

cosΦ, lagging p.f. :

- When the load p.f. is cosΦ lagging, the phase current I_{aph} lags V_{ph} by angle Φ.
- The component F_O is at right angles to V_{ph} while F_{AR} is in phase with the current I_{aph}. This is because the armature current I_{aph} decides the armature reaction.
- The armature reaction F_{AR} due to current I_{aph} is to be overcome by field m.m.f.
- Hence while finding resultant field m.m.f., - F_{AR} should be added to vectorially. This is because resultant field m.m.f. tries to counterbalance armature reaction to produce rated terminal voltage. The phasor diagram is shown in the Fig.



From the phasor diagram the various magnitude are,

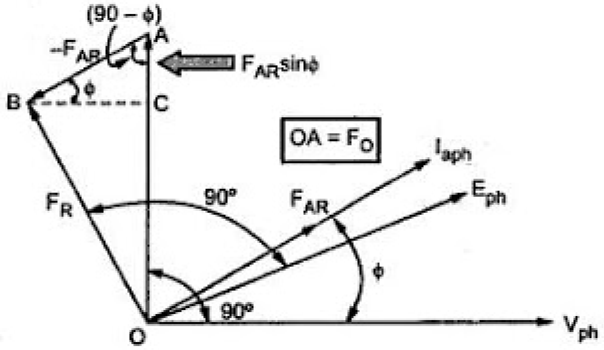
$OA = F_O$, $AB = F_{AR}$, $OB = F_R$

Consider triangle OCB which is right angle triangle. The F_{AR} is split into two parts as,

$AC = F_{AR} \sin\Phi$ and $BC = F_{AR} \cos\Phi$

$\therefore \quad (F_R)^2 = (F_O + F_{AR} \sin\Phi)^2 + (F_{AR} \cos\Phi)^2$ .... (1)

From this relation (1), F_R can be determined.



cosΦ, leading p.f. :

- When the load p.f. is cosΦ leading, the phase current I_{aph} leads V_{ph} by Φ.
- The component F_O is at right angles to V_{ph} and F_{AR} is in phase with I_{aph}.
- The resultant F_R can be obtained by adding - F_{AR} to F_O.
- The phasor diagram is shown in the Fig.

From the phasor diagram, various magnitudes are,

$AC = F_{AR} \sin\Phi$ and $BC = F_{AR} \cos\Phi$

$OA = F_O$, $AB = F_{AR}$ and $OB = F_R$

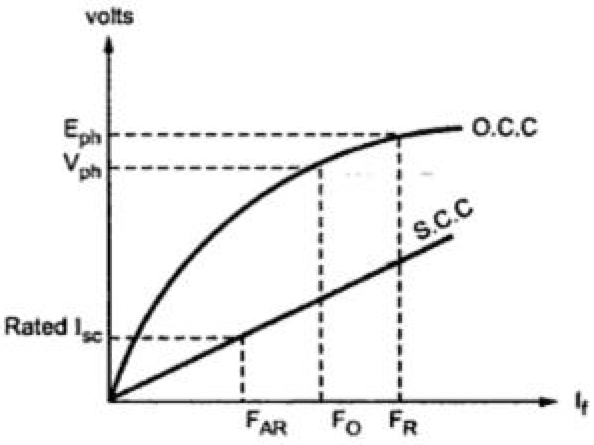
Consider triangle OCB which is right angles triangle.

$\therefore \quad (OB)^2 = (OC)^2 + (BC)^2$

$\therefore \quad (F_R)^2 = (F_O - F_{AR} \sin\Phi)^2 + (F_{AR} \cos\Phi)$ .... (2)

From the relation (2), F_R can be obtained.

Using relations (1) and (2), resultant field m.m.f. F_R for any p.f. load condition can be obtained.



Once F_R is known, obtain corresponding voltage which is induced e.m.f. E_{ph}, required to get rated terminal voltage V_{ph}. This is possible from open circuit characteristics drawn.

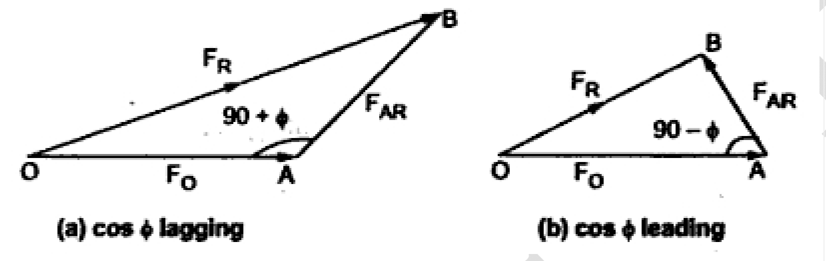
Once E_{ph} is known then the regulation can be obtained as,

$$\% \text{ regulation} = \frac{(\text{Eph}-\text{Vph})}{\text{Vph}} \times 100$$

Note: This ampere-turn method gives the regulation of an alternator which is lower than actually observed. Hence the method is called **optimistic method**.

- When the armature resistance is neglected then F_O is field m.m.f. required to produce rated V_{ph} at the output terminals. But if the effective armature resistance is given then F_O is to be calculated from O.C.C. such that F_O represents the excitation (field current) required a voltage of $V_{ph} + I_{aph} R_{aph} \cos\Phi$ where
  V_{ph} = rated voltage per phase, I_{aph} = full load current per phase
  R_a = armature resistance per phase, $\cos\Phi$ = power factor of the load

F_R can be obtained using the cosine rule to the triangle formed by F_O, F_{AR} and F_O as shown in the Fig. 8.



(a) cos ϕ lagging (b) cos ϕ leading

Using cosine rule to triangle OAB,

$$F_R^2 = F_0^2 + F_{AR}^2 - 2 F_0 F_{AR} \cos (F_0 \,\hat{}\, F_{AR})$$
$$F_0 \,\hat{}\, F_{AR} = 90 + \Phi \text{ if } \Phi \text{ is lagging}$$
$$= 90 - \Phi \text{ if } \Phi \text{ is leading}$$

The angle between E_o and V_{ph} is denoted as δ and is called power angle. Neglecting $R_{a,}$ we can write,

$$I_a X_s \cos\Phi = E_o \sin\delta$$
$$P_d = V_{ph} I_a \cos\Phi = \text{internal power of machine}$$
$$P_d = \frac{V_{ph} E_0}{X_s} \sin \delta$$

C. Potier's Triangle Method or Zero Power Factor (ZPF) Method

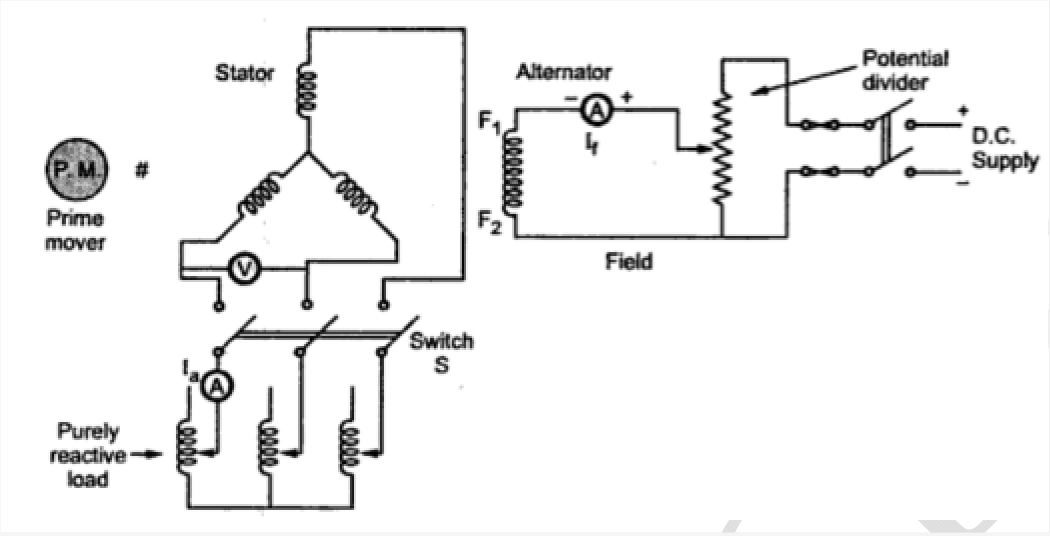
- This method is also called potier method.
- In the operation of any alternator, the armature resistance drop and armature leakage reactance drop IX_L are actually e.m.f. quantities while the armature reaction is basically m.m.f. quantity.
- In the synchronous impedance all the quantities are treated as e.m.f. quantities as against this in M.M.F. method all are treated as m.m.f. quantities. Hence in both the methods, we are away from reality.
- This method is based on the separation of armature leakage reactance and armature reaction effects.
- The armature leakage reactance X_L is called Potier reactance in this method; hence method is also called potier reactance method.

To determine armature leakage reactance and armature reaction m.m.f. separately, two tests are performed on the given alternator. The two tests are,

1. Open circuit test
2. Zero power factor test

1. Open Circuit Test

The experimental setup to perform this test is shown in the Fig.



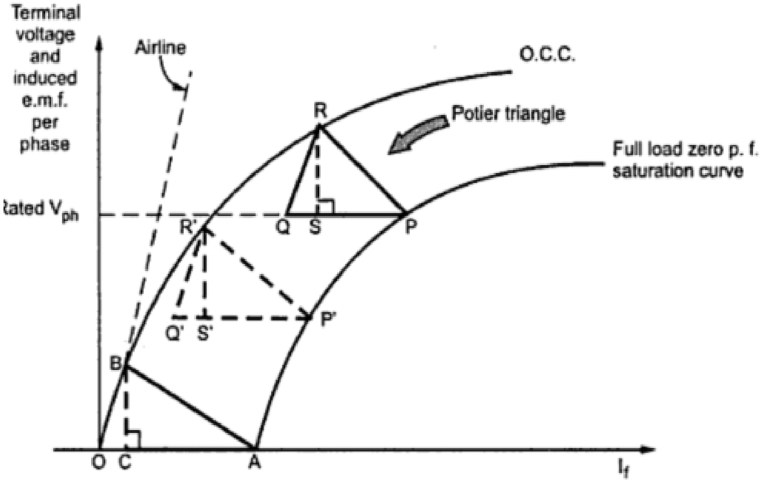
The steps to perform open circuit test are,

- ✓ The switch S is kept open.
- ✓ The alternator is driven by its prime mover at its synchronous speed and same is maintained constant throughout the test.
- ✓ The excitation is varied with the help of potential divider, from zero upto rated value in definite number of steps. The open circuit e.m.f. is measured with the help of voltmeter. The readings are tabulated.
- ✓ A graph of I_f and (V_{oc}) i.e. field current and open circuit voltage per phase is plotted to some scale. This is open circuit characteristics.

2. Zero Power Factor Test

- ✓ To conduct zero power factor test, the switch S is kept closed.
- ✓ Due to this, a purely inductive load gets connected to an alternator through an ammeter. A purely inductive load has power factor of $\cos 90^0$ i.e. zero lagging hence the test is called zero power factor test.
- ✓ The machine speed is maintained constant at its synchronous value.
- ✓ The load current delivered by an alternator to purely inductive load is maintained constant at its rated full load value by varying excitation and by adjusting variable inductance of the inductive load.
- ✓ In this test, there is no need to obtain number of points to obtain the curve. Only two points are enough to construct a curve called zero power factor saturation curve.
- ✓ This is the graph of terminal voltage against excitation when delivering full load zero power factor current.
- ✓ One point for this curve is zero terminal voltage (short circuit condition) and the field current required to deliver the full load short circuit armature current.
- ✓ While other point is the field current required to obtain rated terminal voltage while delivering rated full load armature current. With the help of these two points the zero p.f. saturation curve can be obtained as,

1. Plot open circuit characteristics on graph as shown in the Fig.



2. Plot the excitation corresponding to zero terminal voltage i.e. short circuit full load zero p.f. armature current. This point is shown as A in the Fig. which is on the x-axis. Another point is the rated voltage when alternator is delivering full load current at zero p.f. lagging. This point is P as shown in the Fig.

3. Draw the tangent to O.C.C. through origin which is line OB as shown dotted in the Fig. This is called air line.
4. Draw the horizontal line PQ parallel and equal to OA.
5. From point Q draw the line parallel to the air line which intersects O.C.C. at point R. Join RQ and join PR. The triangle PQR is called potier triangle.
6. From point R, drop a perpendicular on PQ to meet at point S.
7. The zero p.f. full load saturation curve is now be constructed by moving a triangle PQR so that R remains always on O.C.C. and line PQ always remains horizontal. The doted triangle is shown in the Fig. The potier triangle once obtained is constant for a given armature current and hence can be transferred as it is.
8. Through point A, draw line parallel to PR meeting O.C.C. at point B. From B, draw perpendicular on OA to meet it at point C. Triangles OAB and PQR are similar triangles.
9. The perpendicular RS gives the voltage drop due to the armature leakage reactance i.e. IX_L.
10. The length PS gives field current necessary to overcome demagnetising effect of armature reaction at full load.
11. The length SQ represents field current required to induce an e.m.f. for balancing leakage reactance drop RS.

These values can be obtained from any Potier triangle such as OAB, PQR and so on.

So armature leakage reactance can be obtained as,

$$\boldsymbol{L\,(\mathrm{RS}) = l\,(\mathrm{BC}) = (\mathrm{I}_{\mathrm{a\,ph}})_{\mathrm{F.L}}\ \mathrm{x}\ \mathrm{X}_{\mathrm{L\,ph}}}$$

$$\therefore \qquad \mathbf{X}_{\mathbf{L\,ph}} = \frac{\boldsymbol{l}\,(\mathbf{RS})\mathbf{or}\,\boldsymbol{l}\,(\mathbf{BC})}{(\mathbf{I}_{\boldsymbol{a\,ph}}\ )_{\boldsymbol{F.L}}}\ \boldsymbol{\Omega}$$

This is nothing but the potier reactance.

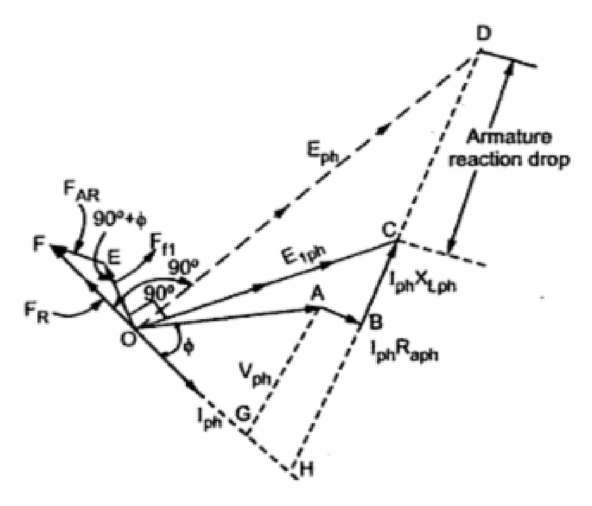
1.3 Use of Potier Reactance to Determine Regulation

To determine regulation using Potier reactance, draw the phasor diagram using following procedure:

- Draw the rated terminal voltage V_{ph} as a reference phasor. Depending upon at which power factor (cosΦ) the regulation is to be predicted, draw the current phasor I_{ph} lagging or leading V_{ph} by angle Φ.
- Draw $I_{ph}\,R_{aph}$ voltage drop to V_{ph} which is in phase with I_{ph}. While the voltage drop $I_{ph}\,X_{Lph}$ is to be drawn perpendicular to $I_{ph}\,R_{aph}$ vector but leading $I_{ph}\,R_{aph}$ at the extremely of V_{ph}.
- The R_{aph} is to be measured separately by passing a d.c. current and measuring voltage across armature winding. While X_{Lph} is Potier reactance obtained by Potier method.

Phasor sum of V_{ph} rated, $I_{ph}\,R_{aph}$ and $I_{ph}\,X_{Lph}$ gives the e.m.f. E_{1ph}.

$$\overline{E_{1\,ph}} = \overline{V_{ph}} + \overline{I_{ph}\ R_{a\,ph}} + \overline{I_{ph}\ X_{L\,ph}}$$



- Obtain the excitation corresponding to $\bar{E}_{1ph}$ from O.C.C. drawn. Let this excitation be $F_{f\,1}$. This is excitation required to induce e.m.f. which does not consider the effect of armature reaction.
- The field current required to balance armature reaction can be obtained from Potier triangle, which is say F_{AR}. ∴ $F_{AR} = l\,(PS) = l\,(AC)$ =.....

The total excitation required is the vector sum of the $F_{f\,1}$ and F_{AR}. This can be obtained exactly similar to the procedure used in M.M.F. method.

Draw vector $F_{f\,1}$ to some scale, leading E_{1ph} by 90^o. Add F_{AR} to F_{f1} by drawing vector F_{AR} in phase opposition to I_{ph}. The total excitation to be supplied by field is given by F_R.

The complete phasor diagram is shown in the Fig.

Once the total excitation is known which is F_R, the corresponding induced e.m.f. E_{ph} can be obtained from O.C.C. This E_{ph} lags F_R by 90^o. The length CD represents voltage drop due to the armature reaction. Drawing perpendicular from A and B on current phasor meeting at points G and H respectively, we get triangle OHC as right angle triangle. Hence E_{1ph} can be determined analytically also.

Once E_{ph} is known, the regulation of an alternator can be predicted as,

$$\% \text{ regulation} = \frac{(Eph - Vph)}{Vph} \times 100$$

This method takes into consideration the armature resistance and leakage reactance voltage drops as e.m.f. quantities and the effect of armature reaction as m.m.f. quantity. This is reality hence the **results obtained by this method are nearer to the reality** than those obtained by synchronous impedance method and ampere-turns method.

The only **drawback** of this method is that the **separate curve for every load condition is necessary** to plot if potier triangles for various load conditions are required.

D. ASA Modification of MMF Method

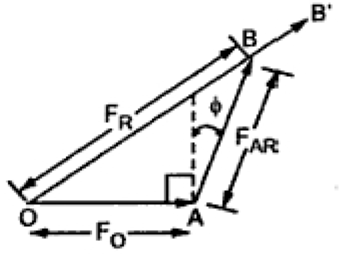
- Neither of the two methods, M.M.F. method and E.M.F. method is capable of giving the reliable values of the voltage regulation.
- The error in the results of these methods is mainly due to the two reasons,

1. In these methods, the magnetic circuit is assumed to be unsaturated. This assumption is unrealistic as in practice. It is not possible to have completely unsaturated magnetic circuit.

2. In salient pole alternators, it is not correct to combine field ampere turns and armature ampere turns.

  - This is because the field winding is always concentrated on a pole core while the armature winding is always distributed.
  - Similarly the field and armature m.m.f.s act on magnetic circuits having different reluctances in case of salient pole machine hence phasor combination of field and armature m.m.f. is not fully justified.

Inspite of these short comings, due to the simplicity of constructions the ASA modified form of M.M.F. method is very commonly used for the calculation of voltage regulation.



- Consider the phasor diagram according to the M.M.F. method as shown in the Fig. for cosΦ lagging p.f. load.
- The F_R is resultant excitation of F_O and F_{AR} where F_O is excitation required to produce rated terminal voltage on open circuit while F_{AR} is m.m.f. required for balancing armature reaction effect.

Thus OB = F_R = resultant m.m.f.

- The angle between F_{AR} and perpendicular to F_O is Φ, where cosΦ is power factor of the load.

But OB = F_R = resultant is based on the assumption of unsaturated magnetic circuit which is not true in practice.

- Actually m.m.f. equal to BB' is additionally required to take into account the effect of partially saturated magnetic field. Thus the total excitation required is OB' rather than OB.

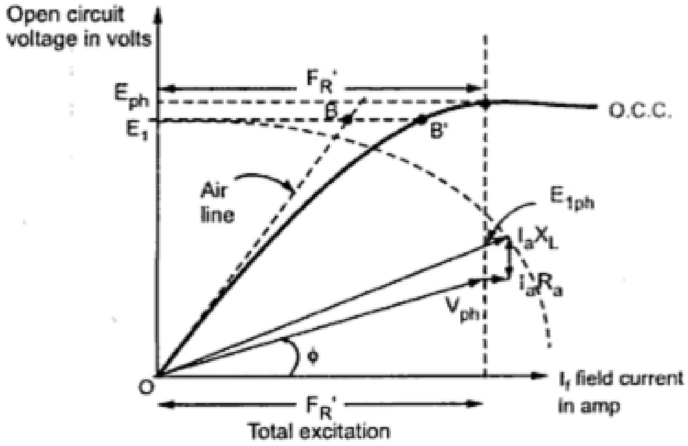
<u>Method of determining the additional excitation needed to take into account effect of partially saturated magnetic circuit.</u>

- Construct the no load saturation characteristics i.e. O.C.C. and zero power factor characteristics.
- Draw the potier triangle and determine the leakage reactance X_L for the alternator.
- The excitation necessary to balance armature reaction can also be obtained from the potier triangle. The armature resistance is known.

$$\overline{E_{1\,ph}} = \overline{V_{ph}} + \overline{I_{ph}\, R_{a\,ph}} + \overline{I_{ph}\, X_{L\,ph}}$$

- Construct ASA diagram, and draw phasor diagram related to the above equation.
- The ASA diagram has x-axis as field current and y-axis as the open circuit voltage.
- Draw O.C.C. on the ASA diagram. Then assuming x-axis as current phasor, draw V_{ph} at angle Φ, above the horizontal. The V_{ph} is the rated terminal voltage.
- Add $I_a R_a$ in phase with I_a i.e. horizontal and $I_a X_L$ perpendicular to $I_a R_a$ to V_{ph}. This gives the voltage E_{1ph}.
- With O as a centre and radius E_{1ph} draw an arc which will intersect y-axis at E_1.

- From E_1, draw horizontal line intersecting both air gap line and O.C.C.
- These points of intersection are say B and B'. The distance between the points BB' corresponding to the field current scale gives the additional excitation required to take into account effect of partially saturated field.
- Adding this to F_R we get the total excitation as F_R'.
- From this F_R', the open circuit voltage E_{1ph} can be determined from O.C.C. using which the regulation can be determined. The ASA diagram is shown in the Fig.

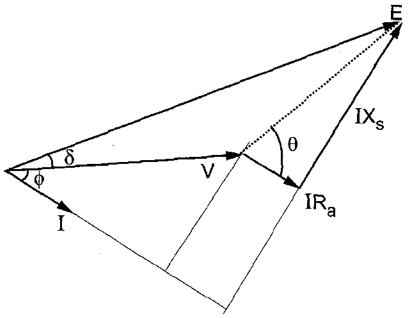


The resultant obtained by ASA method is reliable for both salient as well as non salient pole machines.

THEORY OF CYLINDRICAL ROTOR MACHINES

Let us consider the Phasor diagram for alternator for lagging power factor.

Let E = E.M.F induced in each phase
V = Terminal voltage
Φ = Phase angle between voltage and current
δ = Power angle
Ra = Resistance of armature
X_s = Synchronous reactance of alternator



$$\text{Tan } \theta - \frac{X_s}{R_a}$$

Therefore, $\theta = \tan^{-1}\frac{X_s}{R_a}$

$$\alpha = \Phi + \delta$$

The voltage equation of alternator is given by

$$E = V + IZ_s \qquad \text{i.e.} \qquad I = \frac{E-V}{Z_s}$$

$V = V\angle 0^0$, $E = E\angle\delta$, $Z_s = Z_s\angle\theta$

Therefore $I = \frac{E\angle\delta - V\angle 0^0}{Z_s\angle\theta}$

Electrical power output of alternator

$$P = V.I^* = V\angle 0^0 . \frac{E\angle\delta - V\angle 0^0}{Z_s\angle\theta}{}^* = \frac{E.V}{Z_s}\angle(\theta-\delta) - \frac{V^2}{Z_s}\angle\theta$$

Therefore, $P = \frac{E.V}{Z_s}[\cos(\theta-\delta) + j\sin(\theta-\delta)] - \frac{V^2}{Z_s}[\cos\theta + j\sin\theta]$

Taking real part from above equation,

$$P = \frac{E.V}{Z_s}\cos(\theta-\delta) - \frac{V^2}{Z_s}\cos\theta$$

In case of large machines, $X_s >> R_a$, therefore $\theta = \tan^{-1}\frac{X_s}{R_a} = 90^0$ (R_a neglected)

Substituting $\theta = 90^0$, the net electrical power output is given by

$$P = \frac{E.V}{X_s}\cos(90-\delta) - \frac{V^2}{X_s}\cos 90$$

Therefore, $P = \frac{E.V}{X_s} \sin \delta$

Maximum Power Output

The condition for maximum power output is $\frac{dP}{d\delta} = 0$

Differentiating, we get o + $\frac{E.V}{X_s}$ [-sin(θ-δ)] = 0

$\sin(\theta-\delta) = 0 \qquad (\theta-\delta) = 0 \qquad \text{i.e. } \theta = \delta$

Substituting the condition for maximum output, we get,

$$P_{max} = \frac{E.V}{Z_s}\cos(\theta-\theta) - \frac{V^2}{Z_s}\cos\theta$$

$$P_{max} = \frac{E.V}{Z_s} - \frac{V^2}{Z_s}\cos\theta$$

If R_a is Neglected, $Z_s = X_s$ and $\theta = 90^0$

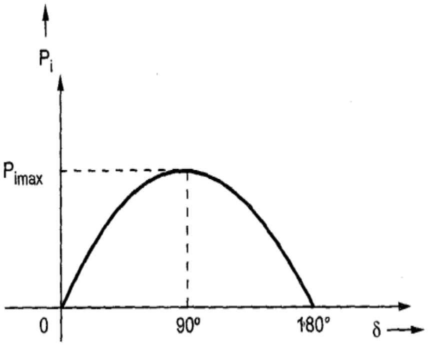
$$P_{max} = \frac{E.V}{X_s} - \frac{V^2}{X_s}\cos 90^0 = \frac{E.V}{X_s}$$

Power Angle Characteristics

$$P = \frac{E.V}{X_s}\sin\delta$$

The relationship between P and δ is known as power angle characteristics of the machine.

The maximum power occurs at δ = 90°. Beyond this point the machine falls out of step and loses synchronism. The machine can be taken upto P_{max} only by gradually increasing the load. This is known as the steady state stability limit of the machine. The machine is normally operated at δ much less than 90°.

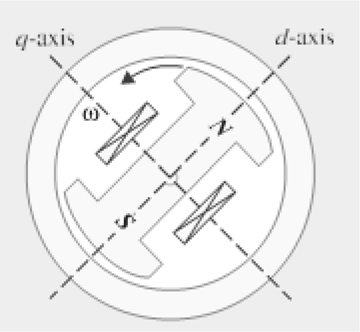


OPERATION OF A SALIENT POLE SYNCHRONOUS MACHINE

- A multipolar machine with cylindrical rotor has a uniform air-gap, because of which its reactance remains the same, irrespective of the spatial position of the rotor.
- A synchronous machine with salient or projecting poles has non-uniform air-gap due to which its reactance varies with the rotor position.
- Consequently, a cylindrical rotor machine possesses one axis of symmetry (pole axis or direct axis) whereas salient-pole machine possesses two axes of geometric symmetry

(i) field poles axis, called direct axis or *d*-axis and

(ii) axis passing through the centre of the interpolar space, called the quadrature axis or *q*-axis, as shown in Fig.



- two mmfs act on the *d*-axis of a salient-pole synchronous machine *i.e.* field m.m.f. and armature m.m.f. whereas only one m.m.f., *i.e.* armature mmf acts on the *q*-axis, because field mmf has no component in the *q*-axis.
- The magnetic reluctance is low along the poles and high between the poles.
- The above facts form the basis of the two-reaction theory proposed by Blondel.

Two Reaction theory

According to this theory

(i) armature current I_a can be resolved into two components
i.e. I_d perpendicular to E_0 and I_q along E_0.

(ii) armature reactance has two components *i.e.* *q*-axis armature reactance X_{ad} associated with I_d and *d*-axis armature reactance X_{aq} linked with I_q.

If the armature leakage reactance X_l is included which is the same on both axes, we get

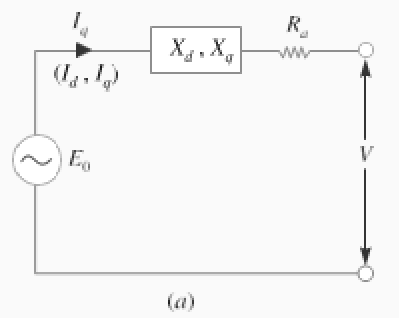
$$X_d = X_{ad} + X_l \text{ and } X_q = X_{aq} + X_l$$

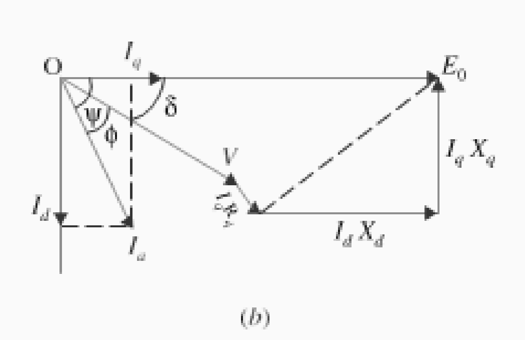
Since reluctance on the q-axis is higher, owing to the larger air-gap, hence,

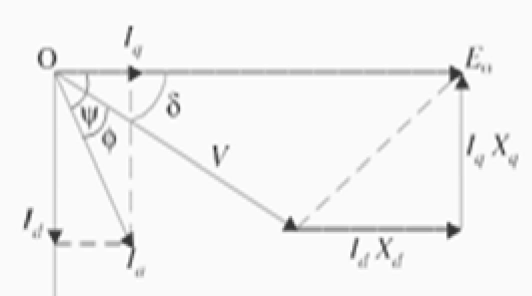
$$X_{aq} < X_{ad} \text{ or } X_q < X_d \text{ or } X_d > X_q$$

Phasor Diagram for a salient pole synchronous machine

- The equivalent circuit of a salient-pole synchronous generator is shown in Fig. (*a*).
- The component currents I_d and I_q provide component voltage drops $jI_d X_d$ and $j I_q X_q$ as shown in Fig. (*b*) for a lagging load power factor.
- The armature current I_a has been resolved into its rectangular components with respect to the axis for excitation voltage E_0.
- The angle ψ between E_0 and I_a is known as the internal power factor angle.
- The vector for the armature resistance drop $I_a R_a$ is drawn parallel to I_a.
- Vector for the drop $I_d X_d$ is drawn perpendicular to I_d whereas that for $I_q X_q$ is drawn perpendicular to I_q.
- The angle δ between E_0 and V is called the power angle.







If Ra neglected

- From Phasor diagram,

$$E_0 = V + I_aR_a + jI_d X_d + jI_q X_q \text{ and } I_a = I_d + I_q$$

If R_a is neglected the Phasor diagram becomes as shown in Fig. In this case,

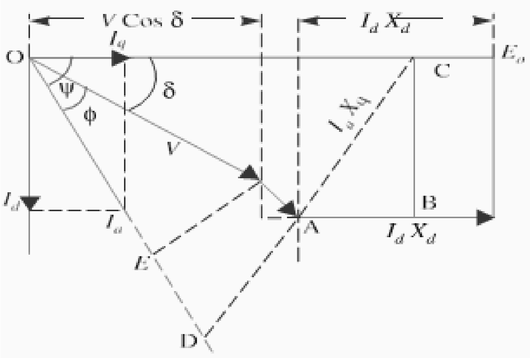
$$E_0 = V + jI_d X_d + jI_q X_q$$

Calculations from Phasor Diagram

- In Fig., dotted line *AC* has been drawn perpendicular to I_a and *CB* is perpendicular to the phasor for E_0.
- The angle *ACB* = ψ because angle between two lines is the same as between their perpendiculars.

$I_d = I_a \sin\psi$; $Iq = I_a \cos\psi$;

Hence, $I_a = Iq/\cos\psi$



In □ *ABC*, *BC*/*AC* = cos ψ or *AC* = *BC*/cos ψ

$$= I_q X_q / \cos\psi$$

$$AC = I_a X_q$$

From ΔODC, ψ can be found by

$$\tan\psi = \frac{AD+AC}{OE+ED} = \frac{V\sin\Phi + IaXq}{V\cos\Phi + IaRa}$$

Then, δ = ψ – Φ

From the Phasor diagram, the excitation voltage is given by

$$E_0 = V\cos\delta + I_q R_a + I_d X_d$$

If we neglect the armature resistance, then δ can be found as below;

$$\psi = \Phi + \delta$$

$$I_d = I_a \sin(\Phi + \delta);\ I_q = I_a \cos(\Phi + \delta)$$

$$V\sin\delta = I_q X_q = I_a X_q \cos(\Phi + \delta)$$

$$= I_a X_q (\cos\Phi\cos\delta - \sin\Phi\sin\delta)$$

$$V = I_a X_q \cot\delta\cos\Phi - IaXq\sin\Phi$$

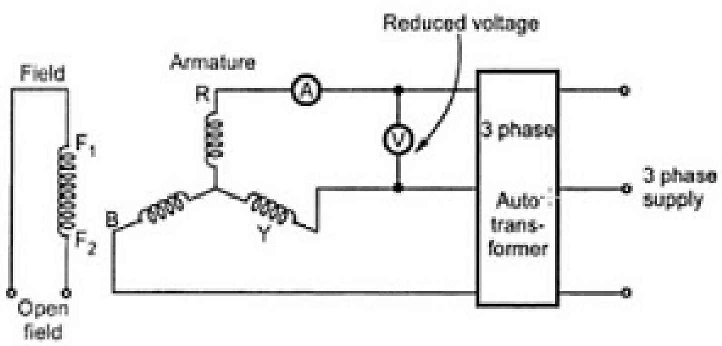
$$I_a X_q \cot\delta\cos\Phi = V + I_a X_q \sin\Phi$$

$$\text{Cot}\,\delta = \frac{V + IaXq\sin\Phi}{IaXq\cos\Phi} \quad \text{or} \quad \tan\delta = \frac{IaXq\cos\Phi}{V + IaXq\sin\Phi}$$

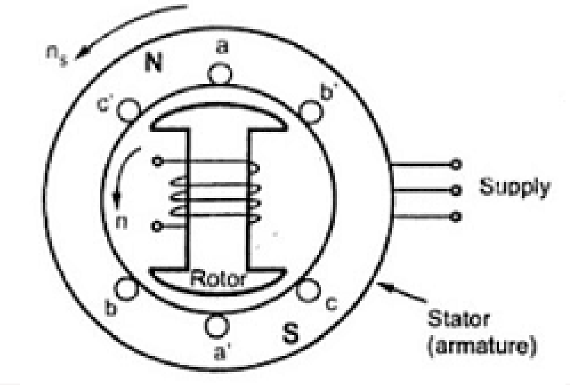
If R_a is neglected, $E_0 = V\cos\delta + I_d X_d$

Determination of X_d and X_q using slip test

- The method used to determine X_q and X_d, the direct and quadrature axis reactance is called slip test.
- In the slip test, a three phase supply is applied to the armature, having voltage must less than the rated voltage while the field winding circuit is kept open. The circuit diagram is shown in the Fig.
- The alternator is run at a speed close to synchronous but little less than synchronous value.
- The three phase currents drawn by the armature from a three phase supply produce a rotating flux.



- Thus the armature m.m.f. wave is rotating at synchronous speed as shown in the Fig.
- The rotor is made to rotate at a speed little less than the synchronous speed.
- Thus armature m.m.f. having synchronous speed, moves slowly past the field poles at a slip speed (n_s -n) where n is actual speed of rotor. This causes an e.m.f. to be induced in the field circuit.
- When the stator m.m.f. is aligned with the d-axis of field poles then flux Φ_d per poles is set up and the effective reactance offered by the alternator is X_d.
- When the stator m.m.f. is aligned with the q-axis of field poles then flux Φ_q per pole is set up and the effective reactance offered by the alternator is X_q.
- As the air gap is non uniform, the reactance offered also varies and hence current drawn the armature also varies cyclically at twice the slip frequency.
- The r.m.s. current is minimum when machine reactance is X_d and it is maximum when machine reactance is X_q.



- As the reactance offered varies due to non uniform air gap, the voltage drops also varies cyclically.
- Hence the impedance of the alternator also varies cyclically. The terminal voltage also varies cyclically.
- The voltage at terminals is maximum when current and various drops are minimum while voltage at terminals is minimum when current and various drops are maximum.
- When rotor field is aligned with the armature m.m.f., its flux linkages are maximum, but the rate of change of flux is zero. Hence voltage induced in field goes through zero at this instant. This is the position where alternator offers reactance X_d.

- While when rate of change of flux associated with rotor is maximum, voltage induced in field goes through its maximum. This is the position where alternator offers reactance X_q.

The reactances can be calculated as

$$X_d = \frac{\text{Maximum voltage}}{\text{Minimum current}} = \frac{\text{(Vt)line (at minimum Ia)}}{\sqrt{3}\ \text{Ia (min)}}$$

$$X_q = \frac{\text{Minimum voltage}}{\text{Maximum current}} = \frac{\text{(Vt)line (at maximum Ia)}}{\sqrt{3}\ \text{Ia (max)}}$$

Power developed by a Salient Pole Alternator (Reluctance Power)

If Ra is neglected, then copper loss is also negligible, then the power developed (P_d) by an alternator is equal to the power output (p_{out}).

Hence per phase power output of an alternator is

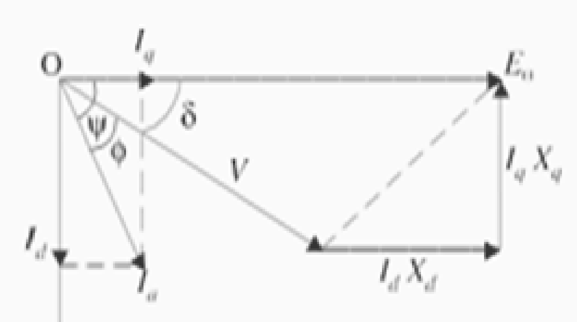
$$P_{out} = V\ I_a \cos\Phi = \text{power developed } (P_d) \qquad \text{.....(i)}$$

From fig., $I_q\ X_q = V \sin\delta$ .....(ii)

$$I_d\ X_d = E_0 - V\cos\delta \qquad \text{... (iii)}$$

$$I_d = I_a \sin(\Phi + \delta) \qquad \text{... (iv)}$$

$$I_q = I_a \cos(\Phi + \delta) \qquad \text{... (v)}$$



If Ra neglected

Substituting Eqn. (iv) and (v) in Eqn. (ii) and (iii) and solving for I_a cosΦ, we get

$$I_a \cos\Phi = \frac{E_0}{X_d}\sin\delta + \frac{V}{2X_q}\sin 2\delta - \frac{V}{2X_d}\sin 2\delta$$

Substituting the above equation in (i), we get

$$P_d = \frac{E_0V}{X_d}\sin\delta + \frac{1}{2}V^2\left(\frac{1}{X_q} - \frac{1}{X_d}\right)\sin 2\delta = \frac{E_0V}{X_d}\sin\delta + \frac{V^2\ (X_d - X_q)}{2\ X_d X_q}\sin 2\delta$$

The total power developed is three times the above power.

The power developed consists of two components,

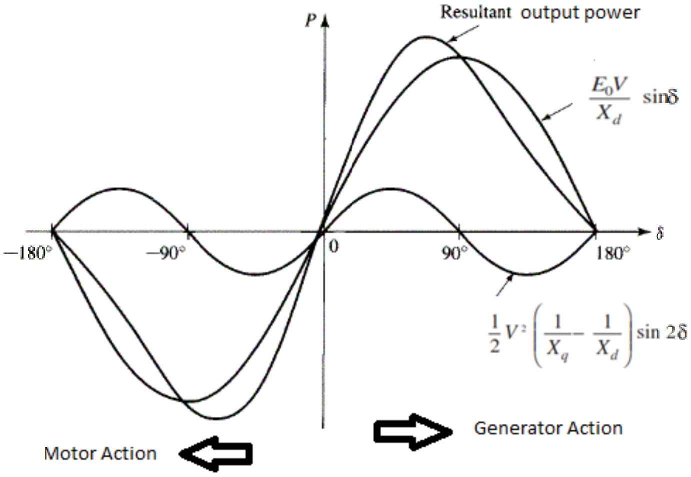
- The first term represents power due to field excitation
- Second term gives the reluctance power i.e. power due to saliency.

If $X_d = X_q$ i.e. the machine has a cylindrical rotor, then the second term is zero and the power is given by the first term only.

Power Angle Characteristics of Salient Pole Alternator

From the output power equation, the power against load angle characteristics can be obtained as shown in the figure.

Condition of δ for maximum power can be obtained by equating dP/dδ = 0 and solving for δ.



Parallel Operation of Alternators

The operation of connecting an alternator in parallel with another alternator or with common bus-bars is known as ***synchronizing***.

Synchronization of alternator and methods of synchronization of alternator

What is meant by synchronization of alternator?

Connecting a group of alternators parallel to a bus bar and the alternators should have same voltage and frequency as that of bus-bar. This is called **synchronization of alternator.**

There are some conditions to be satisfied by the alternators which are to be connected in parallel to bus-bar to be in synchronization.

Conditions for synchronization of alternators:

1. The terminal voltage of incoming alternator must be equal to the bus bar voltage.
2. The frequency of voltage generated by incoming alternator must be equal to bus bar frequency.
3. The phase sequence of the three phases of the incoming alternator must be same as phase sequence of bus-bars.
4. The phase angle between the voltage generated by incoming alternator and voltage of bus-bar must be zero.
5. Always connect running alternator to bus-bar. If a stationary alternator is connected to bus-bar it will result in short circuit of stator winding.

The above conditions are to be satisfied by alternators to satisfy synchronization.

Why synchronization of alternators is necessary?

1. An alternator cannot deliver power to electric power system until its voltage, frequency, phase sequence and other parameters matches with the network to which the alternator is connected.
2. The case of synchronization arises because we are connecting many alternators in parallel to supply the demanded load. So we need to match all the parameters of connected alternators with bus-bar to deliver power to load.
3. By synchronization we can match all the parameters of one alternator with the other alternator and also with the bus-bar and deliver the required power to load.
4. **Synchronization of alternator** is also called as **paralleling of alternators.**

Advantages of paralleling of alternators:

Continuity of service:

In case of any damage to one of the alternators it can be removed. Supply to load is not interrupted because other alternators can supply the required load. But if we use a larger single unit even a small damage causes the interruption of supply.

Requirement of load:

As the load demanded is not same all the time, during light load periods we can run two or three alternators in parallel. When the demand is high we can add the required amount of alternators in parallel to meet the load demanded.

Reliability:

Several single units connected in parallel is more reliable than single larger unit because if a single unit gets damaged it can be removed and its work is compensated by other units which are running.

High efficiency:

An alternator runs efficiently when it is loaded at their rated value. By using required number of alternators for required demand i.e, light load or peak load we can load an alternator efficiently.

Steps to connect alternators in parallel or synchronization of alternators:

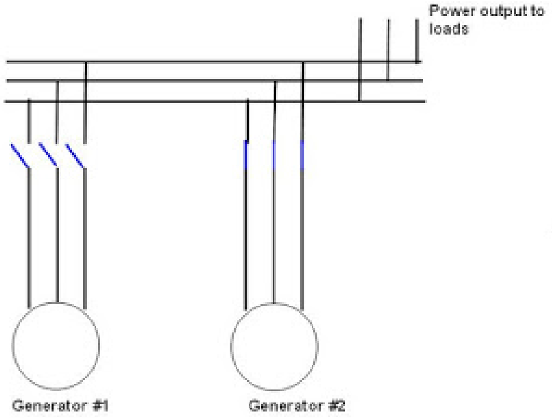
1. Consider an alternator-1. It is supplying power to bus bar at rated voltage and frequency.
2. Now we need to connect another alternator let it be alternator-2 in parallel with the alternator-1. In order to match the frequency of alternator-2 with the frequency of bus-bar or alternator-1 (since alternator-1 and bus-bar are already in synchronism) we need to adjust the speed of alternator-2. Now the voltage of alternator-2 is to be matched with the voltage of bus-bar or voltage of alternator-1 (since alternator-1 and bus-bar are already in synchronism). For this purpose we need to vary the field rheostat until the voltage matches.

3. The three phase voltages generated by alternator must be same as the three phase voltages of bus-bar or alternator-1(since alternator-1 and bus-bar are already in synchronism).This can be achieved by matching the phase sequence and frequency of alternator-2 with bus bar or alternator-1(since alternator-1 and bus-bar are already in synchronism) phase sequence and frequency.

Methods for synchronization of alternators:

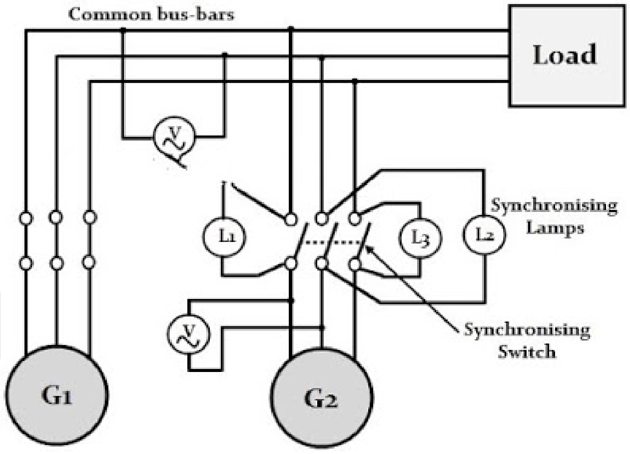
There are three methods for synchronization of alternators. These methods check whether the above mentioned conditions for **synchronization of alternators** are satisfied or not. The three methods are.

1. Three dark lamps method.
2. Two bright, one dark method.
3. Synchroscope method.



Three dark lamps method for synchronization of alternators:

Procedure:



1. Consider alternator-1 is supplying power to load at rated voltage and rated frequency which means alternator-1 is already in synchronism with bus-bar.
2. Now we need to connect alternator-2 in parallel with alternator-1.
3. Across the 3 switches of alternator-2 three lamps are connected as shown in the figure.
4. To match the frequency of alternator-2 with the bus-bar frequency we need to run the prime mover of alternator-2 at nearly synchronous speed which is decided by the frequency of bus-bar and number poles present in alternator-2.
5. To match the terminal voltage of alternator-2 with bus-bar voltage we need to adjust the field current of alternator-2 until terminal voltage of alternator-2 matches with the bus-bar voltage. The required value of voltage can be seen in the voltmeter connected to bus-bar.
6. To know whether the phase sequence of alternator -2 matches with the bus-bar phase sequence we have a condition. If all the three bulbs ON and OFF concurrently then we say the phase sequence of alternator-2 matches with the phase sequence of bus-bar. If the bulbs ON and OFF one after the other then the phase sequence is mismatching.
7. To change the connections of any two leads during the mismatch of phase sequence first off the alternator and change the connections.
8. ON and OFF rate of bulbs depends upon frequency difference of alternator-2 voltage and bus-bar voltage. Rate of flickering of bulbs is reduced when we match the frequency of alternator-2 with bus-bar voltage by adjusting the speed of prime mover of alternator-2.
9. If all the conditions required for synchronization are satisfied then the lamps will become dark.
10. Now close the switches of alternator -2 to synchronize with alternator-1.
11. Now the alternators are in synchronism.

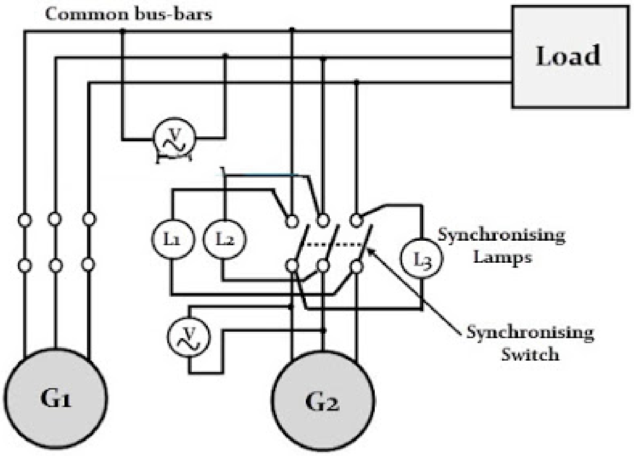
Disadvantage of three dark lamps method for synchronization of alternators:

Flickering only says difference between frequency of voltages of alternator and bus bar but correct value of frequency of voltage of alternator cannot be found.

For example, if the bus bar frequency of voltage is 50 Hz and difference in frequency of voltage of bus-bar and alternator is 1 Hz the alternator frequency of voltage can be either 49 Hz or 51 Hz.

Two bright and one dark lamp method for synchronization of alternators:

Procedure:



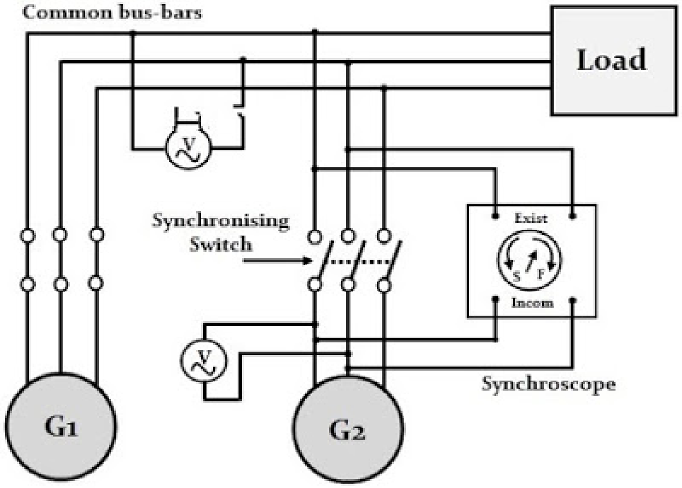
1. Consider alternator-1 is supplying power to load at rated voltage and rated frequency which means alternator-1 is already in synchronism with bus-bar.
2. Now we need to connect alternator-2 in parallel with alternator-1.
3. Here lamp L-2 is connected similar to the **three dark lamp method.**
4. Lamps L-1 and L-3 are connected in different manner. One end of lamp L-1 is connected to one of the phases other that the phase to which lamp L-2 is connected and the other end of lamp L-1 is connected to the phase to which lamp L-3 is connected.
5. Similarly one end of lamp L-3 is connected to a phase other than the phase to which lamp L-2 is connected and other end of lamp L-3 is connected to the phase to which lamp L-1 is connected as shown in the following circuit.
6. To match the terminal voltage of alternator-2 with bus-bar voltage we need to adjust the field current of alternator-2 until terminal voltage of alternator-2 matches with the bus-bar voltage. The required value of voltage can be seen in the voltmeter connected to bus-bar.
7. Depending upon the sequence of lamps L1, L2, L3 becoming dark and bright we can decide whether the alternator-2 frequency of voltage is higher or lower than bus-bar frequency.
8. If the sequence of bright and dark of lamps is L1-L2-L3 then the frequency of voltage of alternator-2 is higher than the bus-bar voltage. Now until the flickering reduces to a low value decreases the speed of prime mover of alternator-2.
9. If the sequence of bright and dark of lamps is L1-L3-L2 then the frequency of voltage of alternator-2 is less than the bus-bar voltage. Now until the flickering reduces to a low value increase the speed of prime mover of alternator-2.
10. When the L1 and L3 are equally bright and lamp L2 is dark then close the switches.
11. Now the alternators are in synchronism.

Disadvantage of two bright and one dark lamp method for synchronization of alternators:

Phase sequence of the alternator cannot be checked by this method.

Synchroscope method for synchronization of alternators:

Procedure:

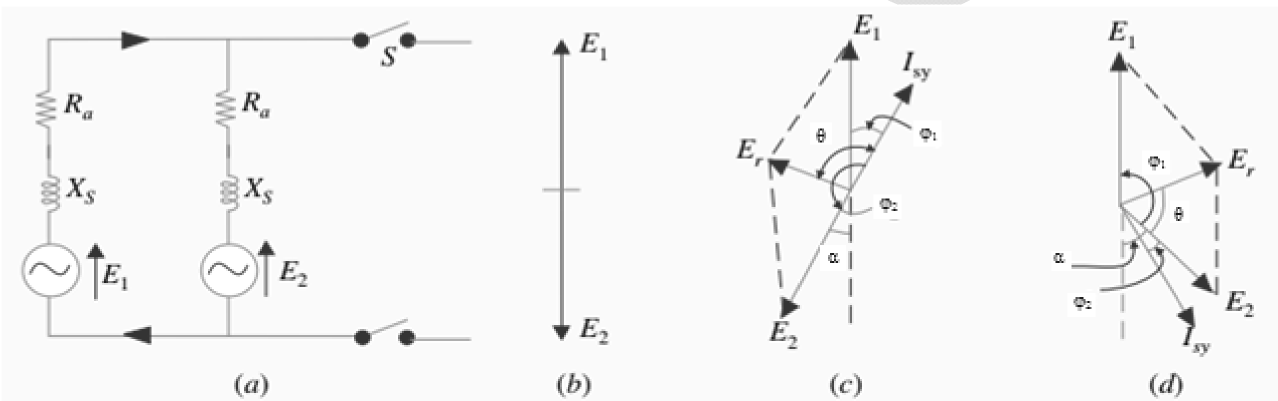


1. A synchroscope is used to achieve synchronization accurately.
2. It is similar to **two bright and one dark lamp method** and tells whether the frequency of incoming alternator is whether higher or lower than bus bar frequency.
3. This contains two terminals they are a) existing terminal b) incoming terminal.
4. Existing terminals are to be connected to bus-bar or existing alternator here in the diagram it is alternator-1 and incoming terminals are connected to incoming alternator which is alternator-2 according to the diagram which we have considered.
5. Synchroscope has a circular dial inside which a pointer is present and it can move both in clockwise and anti clockwise direction.

6. To match the terminal voltage of alternator-2 with bus-bar voltage we need to adjust the field current of alternator-2 until terminal voltage of alternator-2 matches with the bus-bar voltage. The required value of voltage can be seen in the voltmeter connected to bus-bar.
7. Depending upon the rate at which the pointer is rotating the difference of frequency of voltage between incoming alternator and bus-bar can be known.
8. And also if the pointer moves anti clockwise then the incoming alternator is running slower and has frequency less than the bus bar or existing alternator frequency and if the pointer moves clock-wise then the incoming alternator is running faster and has frequency greater than bus-bar or existing alternator frequency. So by adjusting the speed of prime mover of incoming alternator we can match the frequency with bus bar or existing alternator frequency. Frequency matches when the pointer is straight up-wards. At this point close the switch.
9. Now both the alternators are in synchronism.
So by these three methods **synchronization of alternators** is checked.

Synchronizing Current and Synchronizing power

- Once synchronized properly, two alternators continue to run in synchronism.
- Any tendency on the part of one to drop out of synchronism is immediately counteracted by the production of a synchronizing torque, which brings it back to synchronism.
- When in exact synchronism, the two alternators have equal terminal p.d.’s and are in exact phase opposition. Hence, there is no current circulating round the local circuit.



- As shown in Fig. (*b*) e.m.f. E_1 of machine No. 1 is in exact phase opposition to the e.m.f. of machine No. 2 *i.e.* E_2. Hence, there is no resultant voltage.
- Suppose due to change in the speed of the governor of second machine, E_2 falls back by a phase angle of α, as shown in Fig. (*c*) ($E_1 = E_2$). They have a resultant voltage E_r, which circulates a current known as synchronizing current.
- The value of this current is given by $I_{SY} = E_r / Z_S$ where Z_S is the synchronous impedance of the phase windings of both the machines (or of one machine only if it is connected to infinite bus- bars).
- The current I_{SY} lags behind E_r by an angle θ given by $\tan \theta = X_S / R_a$ where X_S is the combined synchronous reactance of the two machines and R_a their armature resistance.
- Since R_a is negligibly small, θ is almost 90 degrees. So I_{SY} lags E_r by 90° and is almost in phase with E_1.
- I_{SY} is generating current with respect to machine No.1 and motoring current with respect to machine No. 2
- This current I_{SY} sets up a synchronizing torque, which tends to retard the generating machine (*i.e.* No. 1) and accelerate the motoring machine (*i.e.* No. 2).
- Similarly, if E_2 tends to advance in phase [Fig. (*d*)], then I_{SY}, being generating current for machine No. 2, tends to retard it and being motoring current for machine No. 1 tends to accelerate it.

- Hence, any departure from synchronism results in the production of a synchronizing current I_{SY} which sets up synchronizing torque. This re-establishes synchronism between the two machines by retarding the leading machine and by accelerating the lagging one.
- Consider Fig. (*c*) where machine No. 1 is generating and supplying the Synchronizing power,

  $P_{SY} = E_1 I_{SY} \cos \varphi_1$

  $\approx E_1 I_{SY}$ (φ_1 is small).

  Since $\varphi_1 = (90° - \theta)$, synchronizing power $= E_1 I_{SY} \cos \varphi_1 = E_1 I_{SY} \cos (90° - \theta) = E_1 I_{SY} \sin \theta \cong E_1 I_{SY}$ because $\theta \cong 90°$ so that $\sin \theta \cong 1$.
- This power output from machine No. 1 goes to supply

  (*a*) Power input to machine No. 2 (which is motoring) and

  (*b*) The Cu losses in the local armature circuit of the two machines.

Power input to machine No. 2 is $E_2 I_{SY} \cos \varphi_2$ which is approximately equal to $E_2 I_{SY}$.

$\therefore E_1 I_{SY} = E_2 I_{SY}$ + Cu losses

Let $E1 = E2 = E$

Then, $E_r = 2E \cos [(180° - \alpha)/2] = 2E \cos [90° - (\alpha/2)] = 2E \sin \alpha/2 = 2E \times \alpha/2 = \alpha E$ ($\because \alpha$ is small)

Here, the angle α is in electrical radians.

Now, $I_{SY} = \dfrac{E_r}{\text{synchronous impedance, } Z_S} \cong \dfrac{E_r}{2X_S} = \dfrac{\alpha E}{2X_S}$

—if R_a of both machines is negligible

X_S - synchronous reactance of one machine

Synchronizing power (supplied by machine No. 1) is

$P_{SY} = E_1 I_{SY} \cos \varphi_1 = E I_{SY} \cos (90° - \theta) = E I_{SY} \sin \theta \cong E I_{SY}$

Substituting the value of I_{SY} from above,

$P_{SY} = E.\alpha E/2Z_S = \alpha E^2/2Z_S \cong \alpha E^2/2X_S$ —per phase

(more accurately, $P_{SY} = \alpha E^2 \sin \theta/2X_S$)

Total synchronizing power for three phases

$= 3P_{SY} = 3\alpha E^2/2X_S$ (or $3\alpha E^2 \sin \theta/2X_S$)

This is the value of the synchronizing power when two alternators are connected in parallel and are on no-load.

Alternators Connected to Infinite Bus-bars

Consider the case of an alternator which is connected to infinite bus-bars.

The expression for P_{SY} given above is still applicable but with one important difference *i.e.* impedance (or reactance) of only that one alternator is considered (and not of two as done above).

Hence, expression for synchronizing power becomes

$E_r = \alpha E$

$I_{SY} = E_r/Z_S \cong E_r/X_S = \alpha E/X_S$ —if Ra is negligible

$\therefore$ Synchronizing power $P_{SY} = E I_{SY} = E.\alpha E/Z_S = \alpha E^2/Z_S \cong \alpha E^2/X_S$ — per phase

Now, $E/Z_S \cong E/X_S$ = S.C. current I_{SC}

$\therefore P_{SY} = \alpha E^2/X_S = \alpha E.E/X_S = \alpha E.I_{SC}$ —per phase

(more accurately, $P_{SY} = \alpha E^2 \sin \theta/X_S = \alpha E.I_{SC}.\sin \theta$)

Total synchronizing power for three phases = $3P_{SY}$

Synchronizing Torque T_{SY}

Let T_{SY} be the synchronizing torque per phase in newton-metre (N-m)

(*a*) When there are two alternators in parallel

$$\therefore \quad T_{SY} \times \frac{2\,\pi\,N_S}{60} = P_{SY} \quad \therefore \quad T_{SY} = \frac{P_{SY}}{2\,\pi\,N_S/60} = \frac{\alpha E^2/2X_S}{2\pi\,N_S/60} \text{ N-m}$$

$$\text{Total torque due to three phases.} = \frac{3P_{SY}}{2\pi N_S/60} = \frac{3\alpha E^2/2X_S}{2\pi N_S/60} \text{ N-m}$$

(*b*) Alternator connected to infinite bus-bars

$$T_{SY} \times \frac{2\pi N_S}{60} = P_{SY} \quad \text{or} \quad T_{SY} = \frac{P_{SY}}{2\pi N_S/60} = \frac{\alpha E^2/X_S}{2\pi N_S/60} \text{ N-m}$$

$$\text{Again, torque due to 3 phase} = \frac{3P_{SY}}{2\pi N_S/60} = \frac{3\alpha E^2/X_S}{2\pi N_S/60} \text{ N-m}$$

where N_S = synchronous speed in r.p.m. $= 120\,f/P$

Effect of Load on Synchronizing Power

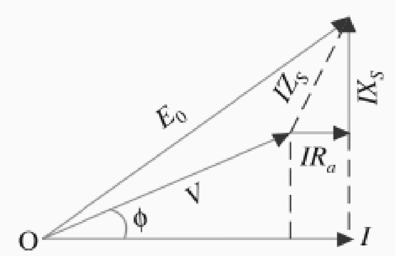
In this case, instead of $P_{SY} = \alpha\, E^2/X_S$, the approximate value of synchronizing power would be $\cong \alpha EV/X_S$

where V is bus-bar voltage and E is the alternator induced e.m.f. per phase.

The value of $E = V + IZ_S$

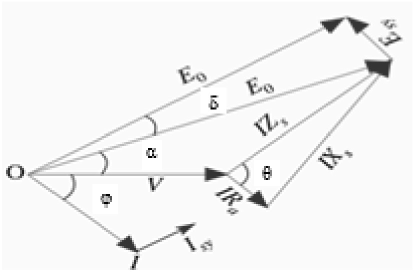
As seen from Fig., for a lagging p.f.,

$E = (V\cos\varphi + IR_a)^2 + (V\sin\varphi + IX_S)^2]^{1/2}$



Alternative Expression for Synchronizing Power

As shown in Fig., let V and E (or E_0) be the terminal voltage and induced e.m.f. per phase of the rotor. Then, taking $V = V\angle 0°$, the load current supplied by the alternator is



$$I = \frac{E - V}{Z_S} = \frac{E\angle\alpha - V\angle 0^0}{Z_S\angle\theta}$$

$$= \frac{E}{Z_S}\angle\alpha\text{-}\theta - \frac{V}{Z_S}\angle\text{-}\theta$$

$$= \frac{E}{Z_S}\,[\cos(\theta - \alpha) - j\sin(\theta - \alpha)] - \frac{V}{Z_S}\,[\cos\theta - j\sin\theta]$$

$$= \left[\frac{E}{Z_S}\cos(\theta - \alpha) - \frac{V}{Z_S}\cos\theta\right] - j\left[\frac{E}{Z_S}\sin(\theta - \alpha) - \frac{V}{Z_S}\sin\theta\right]$$

These components represent the $I\cos\varphi$ and $I\sin\varphi$ respectively. The power P converted internally is given be the sum of the product of corresponding components of the current with $E\cos\alpha$ and $E\sin\alpha$.

$$\therefore \quad P = E\cos\alpha\left[\frac{E}{Z_S}\cos(\theta - \alpha) - \frac{V}{Z_S}\cos\theta\right] - E\sin\alpha\left[\frac{E}{Z_S}\sin(\theta - \alpha) - \frac{V}{Z_S}\sin\theta\right]$$

$$= E\left[\frac{E}{Z_S}\cos\theta\right] - E\left[\frac{V}{Z_S}.\cos(\theta + \alpha)\right] = \frac{E}{Z_S}\,[E\cos\theta - V(\cos\theta + \alpha)] \qquad \text{—per phase}$$

If angle α be changed to $(\alpha \pm \delta)$. Since V is held rigidly constant, due to displacement $\pm\,\delta$, an additional e.m.f. of divergence *i.e.* $I_{SY} = 2E$. Sin $\alpha/2$ will be produced, which will set up an additional current I_{SY} given by $I_{SY} = E_{SY}/Z_S$. The internal power will become

$$P' = \frac{E}{Z_s}\left[E \cos \theta - V \cos (\theta + \alpha \pm \delta)\right]$$

The difference between P' and P gives the synchronizing power.

$$\therefore \quad P_{SY} = P' - P = \frac{EV}{Z_s}\left[\cos (\theta + \alpha) - \cos (\theta + \alpha \pm \delta)\right]$$

$$= \frac{EV}{Z_s}\left[\sin \delta . \operatorname{Sin} (\theta + \alpha) \pm 2 \cos (\theta + \alpha) \sin^2 \delta/2\right]$$

If δ is very small, then $\sin^2 \delta/2$ is zero, hence P_{SY} per phase

$$P_{SY} = \frac{EV}{Z_s} \operatorname{Sin} (\theta + \alpha) \sin \delta \qquad \text{……… (i)}$$

(i) In large alternators, R_a is negligible, hence $\tan \theta = X_s / R_a = \infty$, so that $\theta = 90^0$.

Therefore, $\sin (\theta + \alpha) = \cos \alpha$

$$\therefore \quad P_{SY} = \frac{EV}{Z_s} . \operatorname{Cos} \alpha \sin \delta \quad \text{------per phase} \qquad \text{……… (ii)}$$

$$= \frac{EV}{X_s} . \operatorname{Cos} \alpha \sin \delta \quad \text{------ per phase} \qquad \text{……… (iii)}$$

(ii) Consider the case of synchronizing an unloaded machine on to a constant voltage bus bars. For proper operation, $\alpha = 0$ so that E coincides with V.

$\therefore \quad \sin (\theta + \alpha) = \sin \theta$

From (i), $P_{SY} = \frac{EV}{Z_s} \sin \theta \sin \delta$

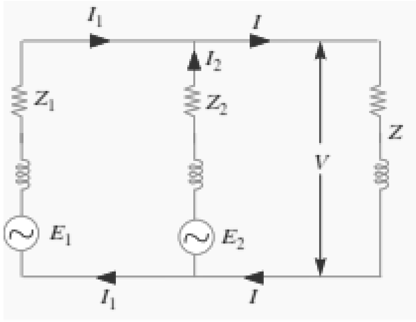
Since δ is very small, $\sin \delta = \delta$

$\therefore \quad P_{SY} = \frac{EV}{Z_s} \delta \sin \theta \quad = \frac{EV}{X_s} \delta \sin \theta$

Usually $\sin \theta = 1$, hence $P_{SY} = \frac{EV}{X_s} \delta = V. \frac{E}{X_s} .\delta = V.I_{SC}.\delta$ --------per phase

Parallel Operation of Two Alternators

Consider two alternators with identical speed/load characteristics connected in parallel as shown in Fig. The common terminal voltage **V** is given by



$V = E_1 - I_1Z_1 = \; = E_2 - I_2Z_2$

$\therefore \quad E_1 - E_2 = I_1Z_1 - I_2Z_2$

Also $\quad I = I_1 + I_2$ and $V = IZ$

$\therefore \quad E_1 = I_1Z_1 + IZ = I_1 (Z + Z_1) + I_2Z$

$$\mathbf{E_2 = I_2Z_2 + IZ = I_2(Z + Z_2) + I_1Z}$$

$$\therefore \quad \mathbf{I_1 = \frac{(E_1 - E_2) Z + E_1Z_2}{Z (Z_1 + Z_2) + Z_1Z_2}}$$

$$\mathbf{I_2 = \frac{(E_2 - E_1) Z + E_2Z_1}{Z (Z_1 + Z_2) + Z_1Z_2}};$$

$$\mathbf{I = \frac{E_1Z_2 + E_2Z_1}{Z (Z_1 + Z_2) + Z_1Z_2}}$$

$$\mathbf{V = IZ = \frac{E_1 Z_2 + E_2Z_1}{Z_1 + Z_2 + (Z_1Z_2/Z)} ; I_1 = \frac{E_1 - V}{Z_1} ; I_2 = \frac{E_2 - V}{Z_2}}$$

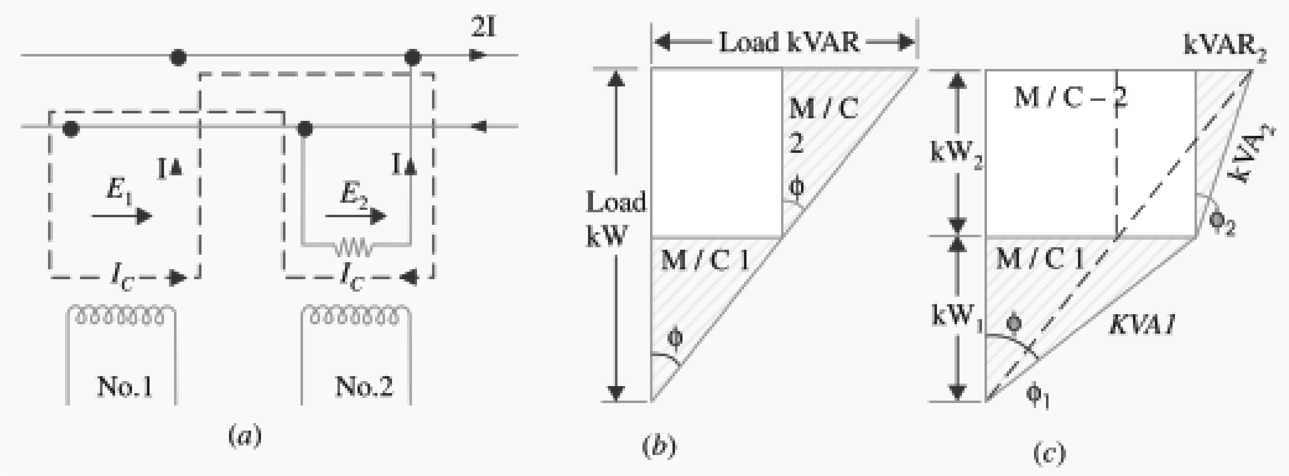
The circulating current under no-load condition is $\mathbf{I_C = (E_1 - E_2)/(Z_1 + Z_2)}$.

Distribution of Load

The amount of load taken up by an alternator running, in parallel with other machines, is solely determined by its driving torque *i.e.* by the power input to its prime mover (by giving it more or less steam, in the case of steam drive). Any alternation in its excitation merely changes its kVA output, but not its kW output. In other words, it merely changes the power factor at which the load is delivered.

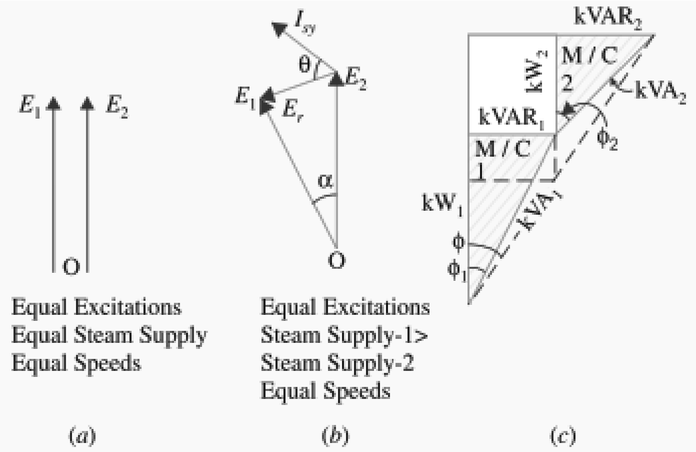
(*a*) Effect of Change in Excitation

- Suppose the initial operating conditions of the two parallel alternators are identical *i.e.* each alternator supplies one half of the active load (kW) and one-half of the reactive load (kVAR), the operating power factors thus being equal to the load p.f.
- In other words, both active and reactive powers are divided equally thereby giving equal apparent power triangles for the two machines as shown in Fig. (*b*).
- As shown in Fig. (*a*), each alternator supplies a load current I so that total output current is $2I$.
- Now, let excitation of alternator No. 1 be increased, so that E_1 becomes greater than E_2.
- The difference between the two e.m.fs. sets up a circulating current $I_C = I_{SY} = (E_1 - E_2)/2Z_S$ which is confined to the local path through the armatures and round the bus-bars.
- This current is superimposed on the original current distribution.
- As seen, I_C is vectorially added to the load current of alternator No. 1and subtracted from that of No. 2.
- The two machines now deliver load currents I_1 and I_2 at respective power factors of cos Φ_1 and cos Φ_2.
- These changes in load currents lead to changes in power factors, such that cos Φ_1 is reduced, whereas cos Φ_2 is increased.
- However, effect on the kW loading of the two alternators is negligible, but kVAR_1 supplied by alternator No. 1 is increased, whereas kVAR_2 supplied by alternator No. 2 is correspondingly decreased, as shown by the kVA triangles of Fig. (*c*).



(*b*) Effect of Change in Steam Supply

- Suppose that excitations of the two alternators are kept the same but steam supply to alternator No. 1 is increased *i.e.* power input to its prime mover is increased.
- Since the speeds of the two machines are tied together by their synchronous bond, machine No. 1 cannot overrun machine No 2.
- Alternatively, it utilizes its increased power input for carrying more load than No. 2.
- This can be made possible only when rotor No. 1 advances its angular position with respect to No. 2 as shown in Fig. (*b*) where E_1 is shown advanced ahead of E_2 by an angle α.
- Consequently, resultant voltage E_r (or E_{sy}) is produced which, acting on the local circuit, sets up a current I_{sy} which lags by almost 90° behind E_r but is almost in phase with E_1 (so long as angle α is small).



- Hence, power per phase of No. 1 is increased by an amount = E_1I_{sy} whereas that of No. 2 is decreased by the same amount (assuming total load power demand to remain unchanged).
- Since I_{sy} has no appreciable reactive (or quadrature) component, the increase in steam supply does not disturb the division of reactive powers, but it increases the active power output of alternator No. 1 and decreases that of No. 2. Load division, when steam supply to alternator No. 1 is increased, is shown in Fig. (*c*).

Points to remember:

1. The load taken up by an alternators directly depends upon its driving torque or in other words, upon the angular advance of its rotor.

2. The excitation merely changes the p.f. at which the load is delivered without affecting the load so long as steam supply remains unchanged.

3. If input to the prime mover of an alternator is kept constant, but its excitation is changed, then kVA component of its output is changed, not kW.

SHORT CIRCUIT TRANSIENTS

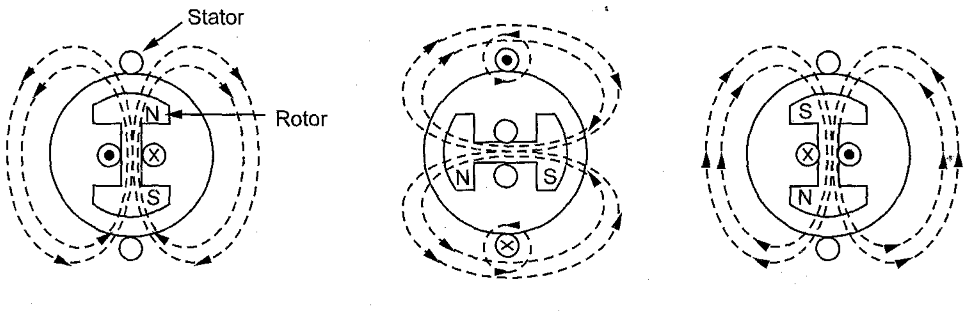
- The alternator running with full excitation may undergo a sudden short circuit because of the abnormal conditions.
- Due to sudden short circuit of alternator, large mechanical forces are developed which may not be sustained by the alternator.
- These forces are proportional to square of the current 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 characteristic time varying behaviour.
- During short circuit, flux pet 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.
- 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.

Constant Flux Linkage 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 = 0.
- If r is very very small then Ldi/dt = 0 or d(Li)/dt = 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 linkage with either winding must remain constant irrespective of the rotation.

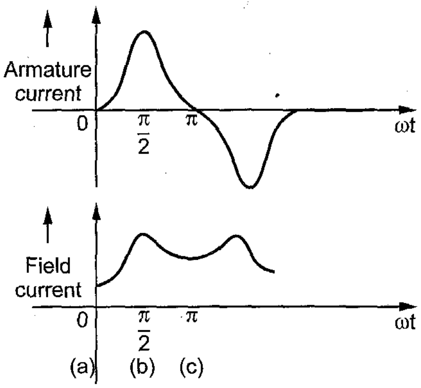
Short Circuit Phenomenon

- Consider a two pole elementary single phase alternator with concentrated stator winding as shown in Fig.
- The corresponding waveforms for stator and rotor currents are shown in the Fig.
- Let short circuit occurs at position of rotor shown in Fig. 3.18.3 (a) when there are no stator linkages.
- After ¼ Rev as shown Fig. (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.



(a) Short circuit instant (b) ¼ Rev after short circuit (c) ½ Rev after short circuit

- 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. changes totally if the position of rotor at the instant of short circuit is different.
- Thus the short circuit current is a function of relative position of stator and rotor.
- 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



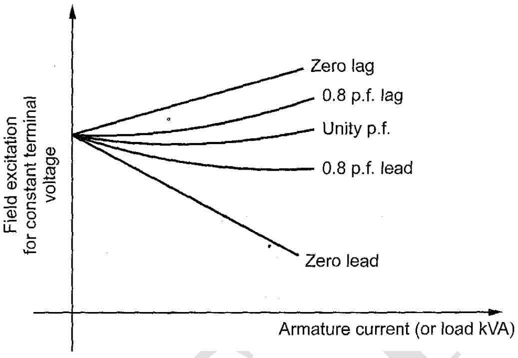
- To maintain the flux linkages constant, the current in rotor reaches to its peak value.
- The stationary field produced by poles on the stator induces a normal frequency emf in the rotor. Thus the rotor current is fluctuating whose resultant a.c. component develops fundamental frequency flux which rotates and again produces in the stator windings 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.

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 e.m.f. 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 but only the leakage 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.

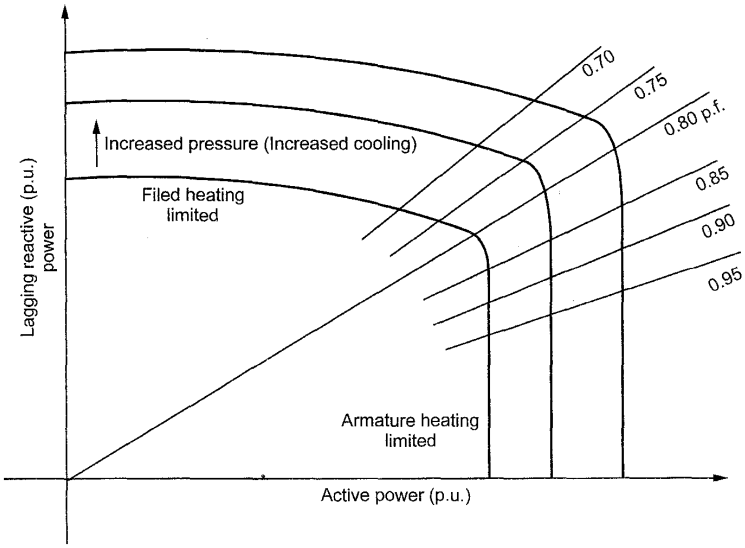
Compounding curve for alternator

If synchronous generator is supplying power at constant frequency to a load whose power factor is constant then curve showing variation of field current versus armature current when constant power factor load is varied is called compounding curve for alternator.



CAPABILITY CURVES

- The ability of prime mover decides the active power output of the alternator which is limited to a value within the apparent power rating.
- The capability curve for synchronous generator specifies the bounds within which it can operate safely.
- The loading on generator should not exceed the generator rating as it may lead to heating of stator.
- The turbine rating is the limiting factor for MW loading.
- The operation of generator should be away from steady state stability limit ($\delta = 90°$).
- The field current should not exceed its limiting value as it may cause rotor heating.
- All these considerations provide performance curves which are important in practical applications.
- A set of capability curves for an alternator is shown in Fig.
- The effect of increased Hydrogen pressure is shown which increases the cooling.
- When the active power and voltage are fixed the allowable reactive power loading is limited by either armature or field winding heating.
- From the capability curve shown in Fig., the maximum reactive power loadings can be obtained for different power loadings with the operation at rated voltage.
- From unity p.f. to rated p.f. (0.8 as shown in Fig.), the limiting factor is armature heating while for lower power factors field heating is limiting factor.



This fact can be derived as follows

- If the alternator is operating at constant terminal voltage and armature current which the limiting value corresponding to heating then the operation of alternator is at constant value of apparent power as the apparent power is product of terminal voltage and current, both of which are constant.
- If P is per unit active power and Q is per unit reactive power then per unit apparent power is given by,

$$\text{Apparent power} = \sqrt{P^2 + Q^2} = V_t \cdot I_a$$

Thus we have,

$$\sqrt{P^2 + Q^2} = V_t \cdot I_a$$

$$\text{Squaring,} \quad P^2 + Q^2 = (V_t \cdot I_a)^2$$

The above equation represents a circle with center at origin and radius equal to $V_t\, I_a$.

- Similarly, considering the alternator to be operating at constant terminal voltage and field current (hence E) is limited to a maximum value obtained by heating limits.

Thus induced voltage E is given by,

$$\bar{E} = \bar{V}_t + \bar{I}_a (R_a + jX_s)$$

If R_a is assumed to be zero then

$$\bar{E} = \bar{V}_t + jX_s \bar{I}_a$$

The apparent power can be written as,

$$P - jQ = \bar{V}_t \cdot \bar{I}_a$$

Substituting value of $\bar{I}_a$

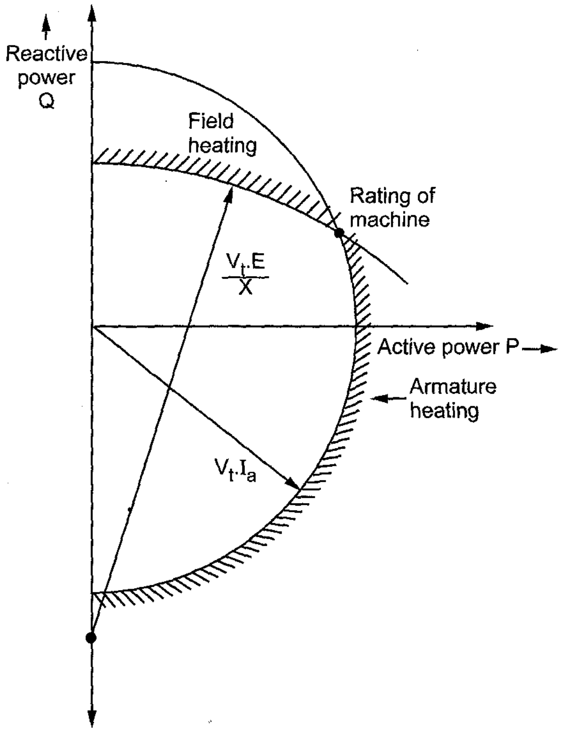
$$P - j\left(Q + \frac{V_t^2}{X_s}\right) = -j\frac{EV_t}{X_s}$$

Taking magnitudes,

$$\sqrt{P^2 + \left(Q + \frac{V_t^2}{X_s}\right)^2} = \frac{EV_t}{X_s}$$

$$\text{Squaring, } P^2 + \left(Q + \frac{V_t^2}{X_s}\right)^2 = \left(\frac{EV_t}{X_s}\right)^2$$

This equation also represents a circle with centre at $\left(0, -\frac{V_t^2}{X_s}\right)$.



These two circles are represented in the Fig. The field heating and armature heating limitations on machine operation can be seen from this Fig. The rating of machine which consists of apparent power and power factor is specified as the point of intersection of these circles as shown in the Fig. So that the machine operates safely.