Polyphase Synchronous Machines

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A three-phase synchronous machine is a doubly excited ac machine becau its field winding is energized from a dc source and its armature windin connected to an ac source. It rotates with speed of revolving field i.e. synchron speed.

Remember:

- In synchronous machine, windings are always connected in star.
- Armature winding is placed in stator and field winding is in rotor.

❑ Synchronous speed

$$\boxed{N_s = \frac{120\,f}{P}}\ \text{rpm}$$

where, f = Frequency of armature current

P = Number of field poles

❑ RMS induced emf per phase

$$\boxed{E_a = 4.44\, f N_e \phi_p}$$

where, N_e = Effective turns per phase

ϕ_p = Total flux linking a full-pitch coil

❑ Effective number of turns

$$\boxed{N_e = N_c k_p k_d}$$

where, N_c = Coil turns

k_d = Distribution factor

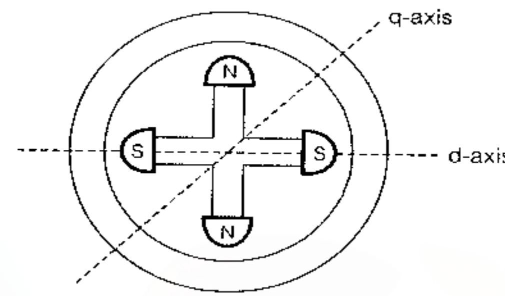
k_p = Pitch factor

❑ Winding factor

$$\boxed{k_\omega = k_p k_d}$$

Types of Rotor

(a) Salient Pole Rotor



- Salient pole windings are concentrated winding and connected in series.
- d-axis and q-axis are 90° electrical to each other.
- Air gap is minimum along d-axis and maximum along q-axis.
- Salient pole machine drives at low speed and hence is called as low speed alternator or hydro alternator.
- Salient pole rotor has large diameter and small axial length.

Remember:

Salient pole alternator also called as hydro alternator.

(b) Cylindrical Rotor

- Field winding is distributed and all coils are connected in series.
- Air gap is uniform.
- It can be driven at high speed so it is also known as high speed alternator or turbo generator.
- Cylindrical rotor has smaller diameter and larger axial length.

Note:

- In alternator, main field mmf leads the air-gap mmf and air-gap mmf leads the armature mmf. Therefore, in alternator main field mmf is most leading.
- In motor, main field mmf lags the air-gap mmf and air-gap mmf lags the armature mmf. Therefore, in motor main field mmf is most lagging.
- For unidirection torque production, number of rotor poles must be equal to number of stator poles and they must be stationary with respect to each other.

Armature Reaction

The effect of armature flux (ϕ_a) on main field flux (ϕ_m) is known as armature reaction. Armature reaction depends upon the magnitude of load and load power factor.

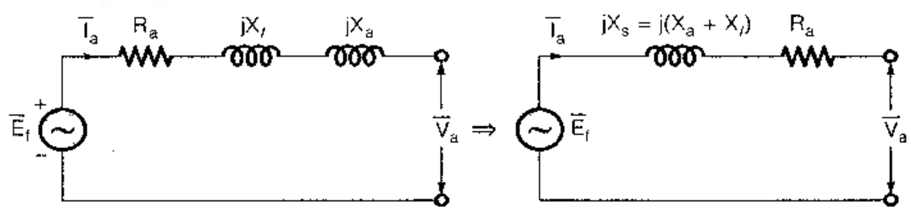
P.F.	Alternator	Motor
1. Unity	Purely cross magnetizing	Purely cross magnetizing
2. ZPF lag	Purely demagnetizing	Purely magnetizing
3. ZPF lead	Purely magnetizing	Purely demagnetizing
4. 0.8 lag	Partly demagnetizing + Partly cross magnetizing	Partly magnetizing+ Partly cross magnetizing
5. 0.8 lead	Partly magnetizing + Partly cross magnetizing	Partly demagnetizing + Partly cross magnetizing

Synchronous Generator Model:

$$\boxed{\bar{E}_f = \bar{V}_a + \bar{I}_a R_a - \bar{E}_l - \bar{E}_{ar}}$$

$$\boxed{\bar{E}_f = \bar{V}_a + \bar{I}_a R_a + j\bar{I}_a X_l + j\bar{I}_a X_a}$$

where,
- $\bar{E}_f$ = Excitation voltage or internal voltage
- $\bar{E}_{ar}$ = Armature reaction voltage
- $\bar{E}_l$ = Armature leakage flux voltage
- R_a = Armature resistance
- X_l = Armature leakage reactance
- X_a = Armature reaction reactance
- $\bar{I}_a$ = Armature current
- $\bar{V}_a$ = Terminal voltage



$$\boxed{\bar{E}_f = \bar{V}_a + \bar{I}_a R_a + j\bar{I}_a X_s}$$

where, $X_s = X_l + X_a$ = synchronous reactance

$$\boxed{\bar{E}_f = \bar{V}_a + \bar{I}_a \bar{Z}_s}$$

where, $Z_s = (R_a + jX_s)$ = synchronous impedance

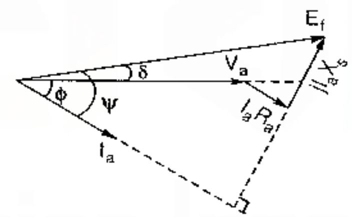
Drop in Voltage

- Drop due to armature resistance i.e. $I_a R_a$.
- Drop due to armature leakage reactance i.e. $I_a x_l$ (due to armature leakage flux).
- Drop due to armature reaction i.e. $I_a x_a$.

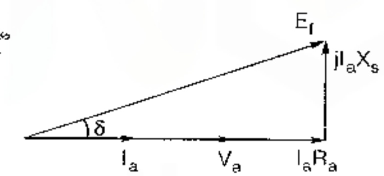
Remember:

- The terminal voltage of an a.c. generator depends upon the load and may be larger or smaller than the generated voltage.
- The terminal voltage may actually be higher than the generated voltage when the power factor is leading.
- For unity and lagging power factor, the terminal voltage is smaller than the generated voltage.

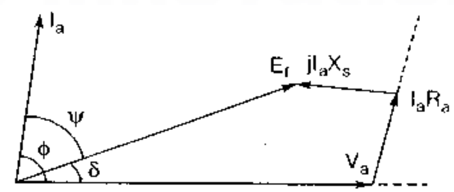
Phasor diagram



Lagging p.f.



Unity p.f.



Leading p.f.

Note:

- When $E_f \cos\delta = V_a$ normal excitation (unity p.f.)
- When $E_f \cos\delta > V_a$ Over excited machine (lagging p.f.)
- When $E_f \cos\delta < V_a$ Under excited machine (leading p.f.)

Synchronous generator tests and characteristics

Resistance test

- Per phase resistance

  for star connected generator

$$\boxed{R_a = 0.5 R_L}$$

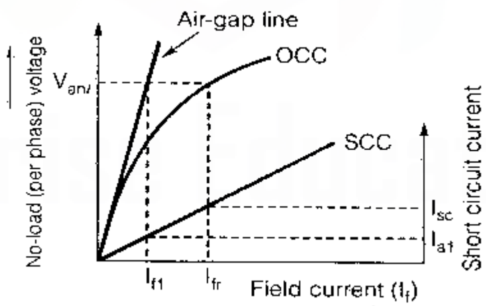
  for delta connected generator

$$\boxed{R_a = 1.5 R_L}$$

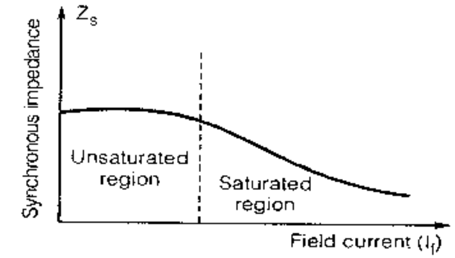
where, R_L = measured value of resistance

Open circuit and Short circuit characteristics

- Find the value of the field current (I_{fr}) that gives the rated per-phase voltage (V_{anL}) from the OCC of the generator.
- Find the value of the short-circuit current (I_{sc}) from the SCC for the same value of the field current I_{fr}.



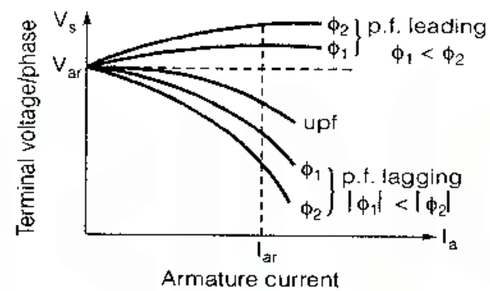
- Synchronous impedance



$$\boxed{Z_s = \frac{\text{Open circuit terminal voltage for a certain field current}}{\text{Short-circuit current for the same field current}}}$$

$$\boxed{Z_s = \frac{V_{anL}}{I_{sc}}}$$

External characteristics



Short Circuit Ratio (SCR)

SCR is defined as ratio of field current required to produce rated voltage on open circuit to the field current required to produce rated armature current on short circuit.

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

$$\boxed{SCR = \frac{I_{SC}}{I_{rated}} = I_{SC\,(p.u.)}}$$

$$\boxed{SCR = \frac{1}{X_{s(saturated)\ p.u.}}}$$

Remember:

- For hydro generator SCR is high.
- For turbo generator SCR is low.
- A synchronous machine with high value of SCR has a better voltage regulation and improved steady-state stability limit but short circuit fault current in armature is high.
- A machine with low SCR is less stable when operating in parallel with other generators. But the armature current under short circuit conditions is small.

Voltage Regulation

Voltage regulation is defined as, rise in voltage expressed as a fraction of full load rated voltage when full load is thrown off, while keeping the excitation constant.

$$\text{Regulation} = \frac{|E_f| - |V_a|}{|V_a|}$$

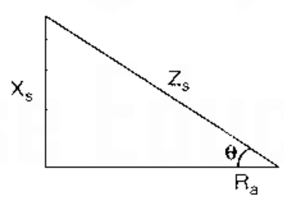
$$\text{Regulation} \propto Z_s$$

Remember:

- Order of voltage regulation in alternator is 30 to 40%.

For minimum voltage regulation

Zero voltage regulation is possible only for leading p.f. load.



For zero regulation:

$$\cos(\theta + \phi) = \frac{-I_a Z_s}{2V} \quad \text{or} \quad \theta + \phi = 90°$$

where, θ = Impedance angle

ϕ = Power factor angle

Maximum voltage regulation

Maximum regulation is possible only for lagging pf load.

For maximum regulation:

$$\text{Load p.f. angle } (\phi) = \text{Impedance angle } (\theta)$$

Remember:

- Voltage regulation is always positive for resistive load or U.P.F. load or lagging p.f. load.
- Voltage regulation could be positive (for high leading p.f.), zero and negative for leading p.f. load.

Voltage Regulation Method

1. **Synchronous Impedance Method (EMF Method)**

   Here we assume drop due to armature reaction is considered drop due to leakage reactance. It gives regulation more then the actual value and hence it is called as pessimistic method.

2. **M.M.F. Method (Amp-turn method)**

   Here, we assume drop due to leakage reactance is considered as drop due to armature reaction. This method gives regulation less than actual value therefore it is called as optimistic method.

3. **Z.P.F. Method**

   Plot of V_a versus I_f corresponding to different field current. For maintaining rated armature current at zero p.f. lag called ZPF characteristic or potier triangle characteristic.

4. **A.S.A. Method**

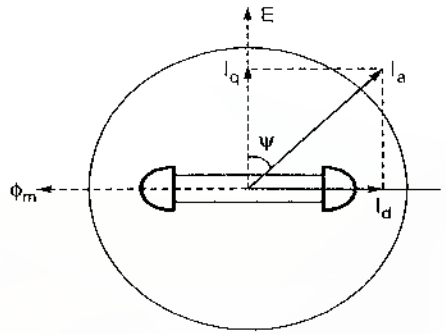
   Here effect of saturation is also considered. This method is combination of Z.P.F. and M.M.F. method.

Note:

Voltage regulation: EMF > ASA > ZPF > MMF.

Two Reaction Theory

This theory is applicable to salient pole machines only.

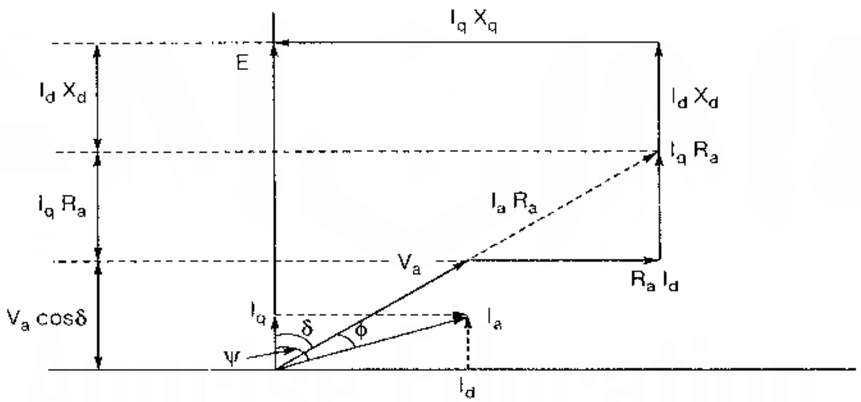


$$\boxed{I_d = I_a \sin\psi}$$

$$\boxed{I_q = I_a \cos\psi}$$

where, I_d = Direct axis armature current

I_q = Quadrature axis armature current



$$\boxed{E = V_a \cos\delta + I_q R_a \pm I_d X_d}$$

$$\boxed{\tan\psi = \frac{V_a \sin\phi \pm I_a X_q}{V_a \cos\phi + I_a R_a}}$$

$$\boxed{\psi = \delta \pm \phi}$$

here, + sign for lagging p.f. and sign for leading p.f.

where, ψ = internal pf angle by which I_a lags E.

δ = Load angle between E and V

ϕ = Power factor angle between V_a and I_a

- If R_a neglected as $R_a << X_s$.

$$\boxed{I_d = \frac{E - V_a \cos\delta}{X_d}} \quad \text{and} \quad \boxed{I_q = \frac{V_a \sin\delta}{X_q}}$$

- Per Phase Power

$$\boxed{P = \underbrace{\frac{EV_a}{X_d}\sin\delta}_{\text{Electromagnetic power}} + \underbrace{\frac{V_a^2}{2}\left(\frac{1}{X_q} - \frac{1}{X_d}\right)\sin 2\delta}_{\text{Reluctance power } (P_{rel.})}}$$

Remember:

- In cylindrical rotor, P_{rel} is zero since it does not have saliency and $X_d = X_q = X_s$.
- Reluctance power is generated only when machine is connected to or operating on infinite bus bar.

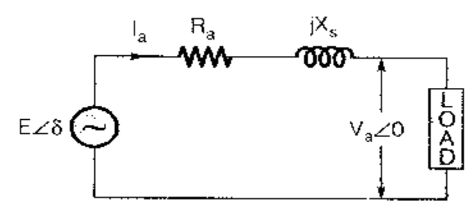
Slip Test

From slip test, the direct and quadrature axis synchronous reactances i.e. X_d and X_q can be determined.

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

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

Power Flow in Alternator



Complex power output

$$S = P + jQ = V_a I_a^*$$

$$\boxed{P = \frac{EV_a}{Z_s}\cos(\theta - \delta) - \frac{V_a^2}{Z_s}\cos\theta}$$

$$\boxed{Q = \frac{EV_a}{Z_s}\sin(\theta - \delta) - \frac{V_a^2}{Z_s}\sin\theta}$$

If, $R_a = 0$ then $Z_s = X_s$ and $\theta = 90°$

$$\boxed{P = \frac{EV_a}{X_s}\sin\delta}$$

$$\boxed{Q = \frac{V_a}{X_s}[E\cos\delta - V]}$$

- Condition for maximum power output i.e. $\frac{dP}{d\delta} = 0$

$$\boxed{\text{impedance angle } (\theta) = \text{load angle } (\delta)}$$

Note: ....

Always replace δ by θ.

....

$$\boxed{P_{max} = \frac{EV_a}{Z_s} - \frac{V_a^2}{Z_s}\cos\theta}$$

Power relationship

- Mechanical power input to the generator

$$\boxed{P_{in,m} = T_s\,\omega_s}$$

- D.C. power input to a wound rotor

$$\boxed{P_{in,e} = V_f I_f}$$

- Total power input

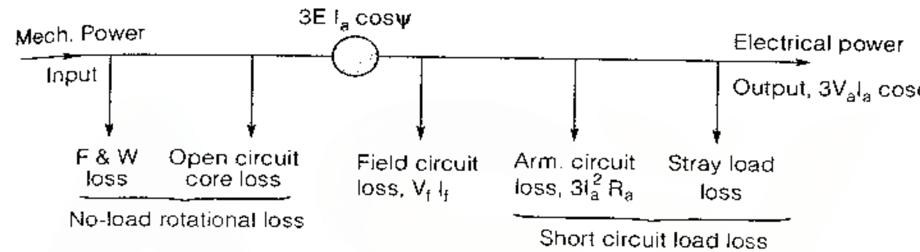
$$\boxed{P_{in} = T_s\,\omega_s + V_f I_f}$$

- Power output of a synchronous generator

$$\boxed{P_o = 3V_a I_a \cos\phi}$$

- Copper loss in armature winding

$$\boxed{P_{cu} = 3I_a^2 R_a}$$



- Total power input to synchronous generator

$$\boxed{P_{in} = 3V_a I_a \cos\phi + 3I_a^2 R_a + P_r + P_{st} + V_f I_f}$$

where, P_r = Rotational losses of synchronous generator

P_{st} = Stray load losses

- Constant losses

Since the rotor revolves at a constant speed, the rotational loss is constant. The field-winding loss is constant. Assuming the stray-load loss to be a constant.

$$\boxed{P_c = P_r + P_{st} + V_f I_f}$$

Efficiency

- Efficiency of the generator

$$\boxed{\eta = \frac{3V_a I_a \cos\phi}{3V_a I_a \cos\phi + P_c + 3I_a^2 R_a}}$$

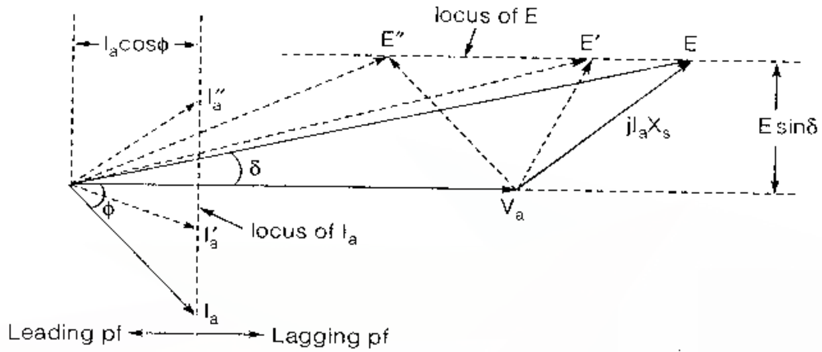
For the maximum efficiency

$$\boxed{3I_a^2 R_a = P_c}$$

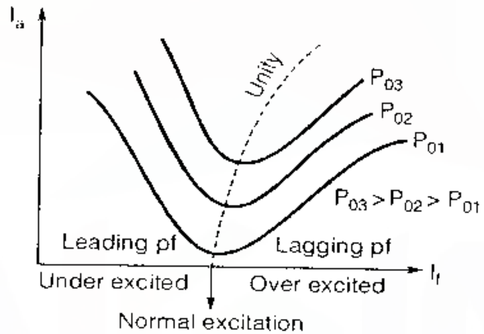
Condition that must be satisfied for parallel operation

- Terminal voltage of incoming alternator should be equal to existing system and that can be done by varying excitation.
- Frequency of incoming alternator should be equal to existing system. Frequency is maintained same by adjusting primover speed.
- Phase sequency of incoming alternator must be same as that of existing system.

Constant power loci of armature current with generated voltage

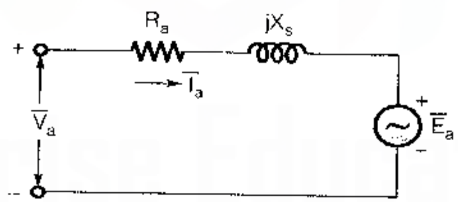


V curves



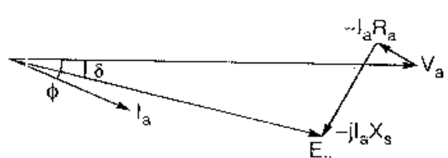
Round-Rotor synchronous motors

Equivalent circuit



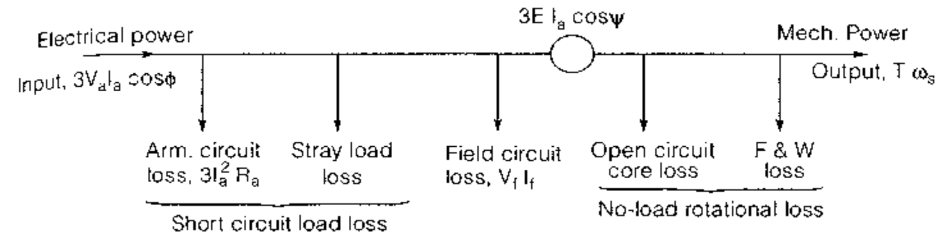
$$\bar{V}_a = \bar{E}_a + \bar{I}_a R_a + j\bar{I}_a X_s$$

Phasor diagram



(Lagging p.f.)

Power flow diagram



- Average power input

$$P_{in} = 3\,V_aI_a\cos\phi + V_fI_f$$

- Total copper loss

$$P_{cu} = 3I_a^2R_a$$

- Power developed

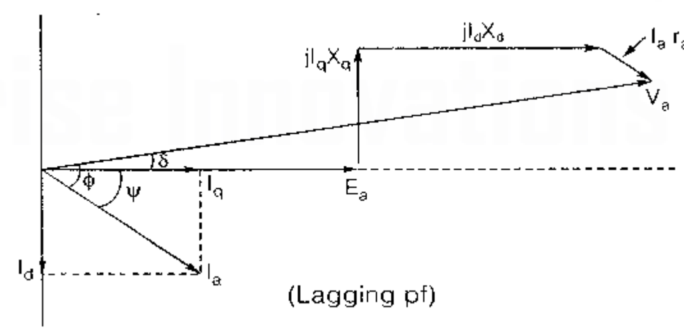
$$P_d = 3\,V_aI_a\cos\phi - 3I_a^2R_a - V_fI_f - \text{stray load loss}$$

Salient-pole synchronous motor

$$V_a = E_a + I_aR_a + jI_dX_d + jI_qX_q \quad \text{or}$$

$$\bar{E}_a = \bar{V}_a - \bar{I}_aR_a - j\bar{I}_aX_q - j\bar{I}_d(X_d - X_q)$$

Phasor diagrams



(Lagging pf)

- Power developed

$$P_d = \frac{3V_aE_a\sin\delta}{X_d} + \frac{3}{2}V_a^2\sin 2\delta\left[\frac{X_d - X_q}{X_dX_q}\right]$$

- Power developed owing to field excitation

$$P_{df} = \frac{3V_aE_a}{X_d}\sin\delta$$

- Power developed due to the saliency of rotor

$$P_{ds} = 3V_a^2\left(\frac{X_d - X_q}{2X_dX_q}\right)\sin 2\delta$$

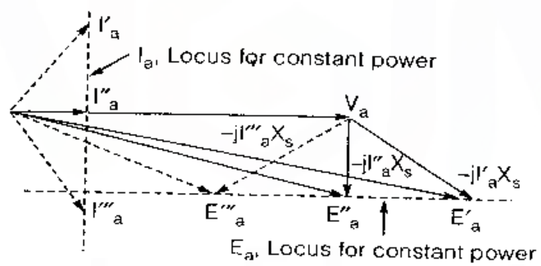
Condition for maximum power

$$\tan\delta_m = \frac{X_s}{R_a}$$

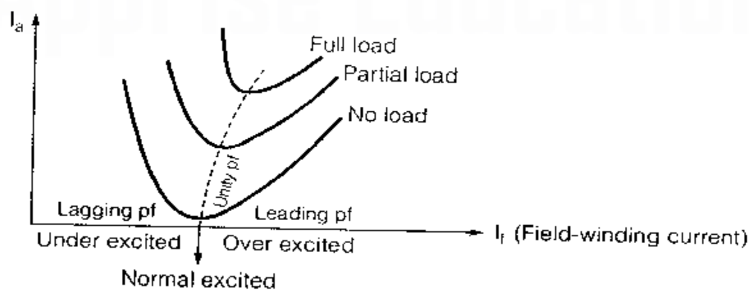
- Per-phase maximum power developed

$$P_{dma} = \frac{V_aE_a}{Z_s} - \frac{E_a^2R_a}{Z_s^2}$$

Constant power loci of armature current and excitation voltage



V curves



Starting of Synchronous Motors

A synchronous motor is not self-starting. It can be started by the following two methods:

- Starring with the help of an external prime mover.
- Starting with the help of damper windings.

Hunting or Phase Swinging

The phenomenon of oscillation of rotor about its final equilibrium position is called hunting. Since during rotor oscillations, the phase of the phasor E_f changes relation to phasor V hunting is known as phase swinging.

Hunting occurs not only in the synchronous motors but also in synchronous generators upon the abrupt change in loading.

Synchronous Condenser

It is a synchronous motor running without a mechanical load which can generate on absorb reactive VAr by varying the excitation of its field winding.

Remember:

- Since, a synchronous condenser behaves like variable inductor or a variable capacitor, it is used in power transmission systems to regulate line voltage.
- They are also used in constant speed applications.

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