AC Machines: Synchronous Machine

Theory of salient pole machine: Blondel's two reaction theory

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Rotor Construction

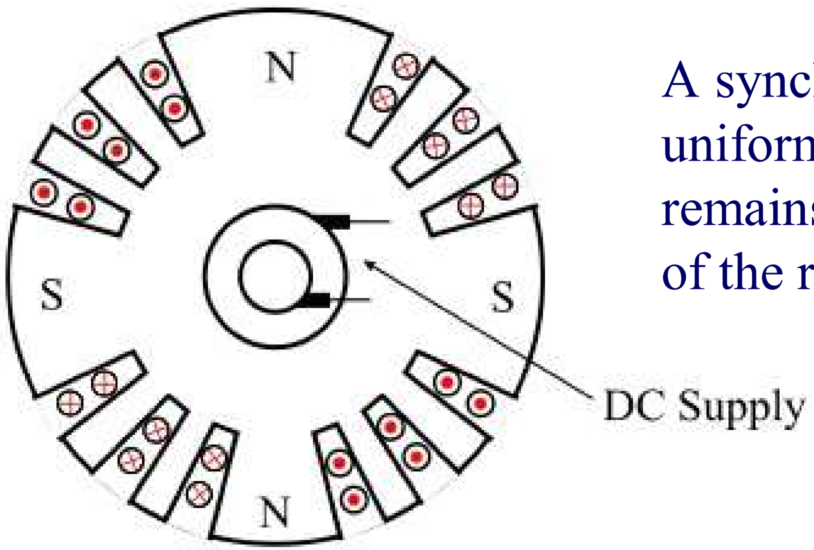


Fig. - Cylindrical Rotor

A synchronous 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 cylindrical rotor machine possesses one axis of symmetry

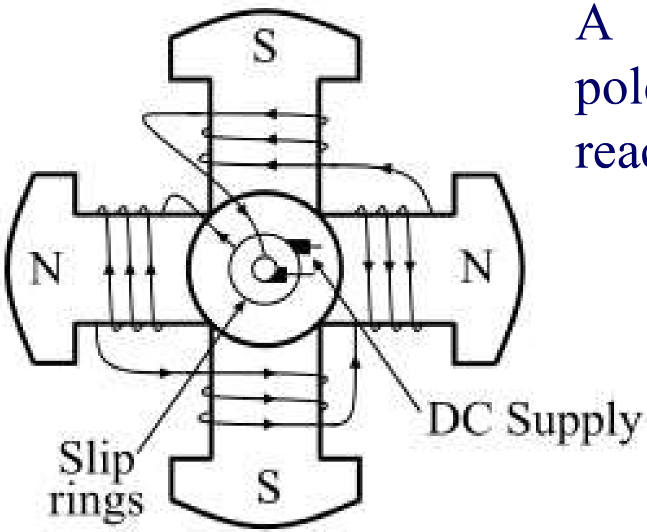


Fig. - Salient Pole Rotor

A synchronous machine with salient or projecting poles has non-uniform air-gap due to which its reactance varies with the rotor position.

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 *qaxis*

Two Reaction Theory of Salient Pole Machine

- In a salient-pole rotor synchronous machine, the air-gap is highly non-uniform.
- The axis shown along the axis of the rotor is known as *direct axis or d-axis* and the axis perpendicular to the d-axis is called *quadrature axis or q-axis*.
- Small air-gaps are involved in the path of d-axis flux (φd), thus the reluctance of the path is minimum
- The q-axis flux (φq) path has large air-gaps and it is the path of maximum reluctance.

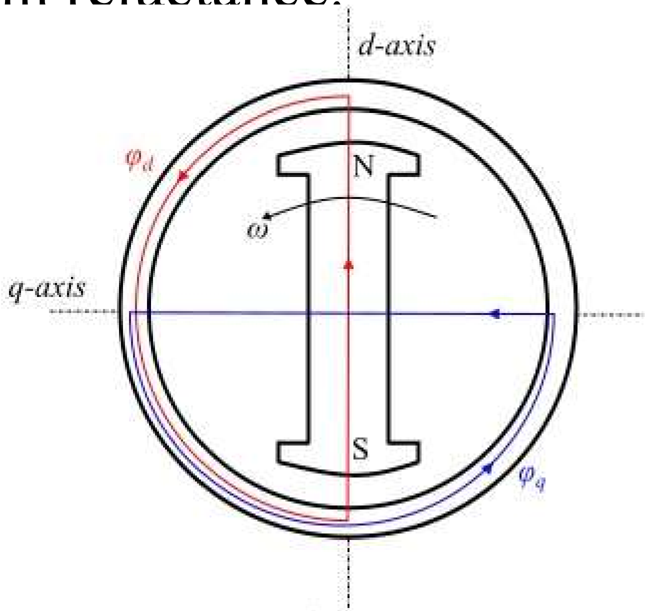


Figure-1

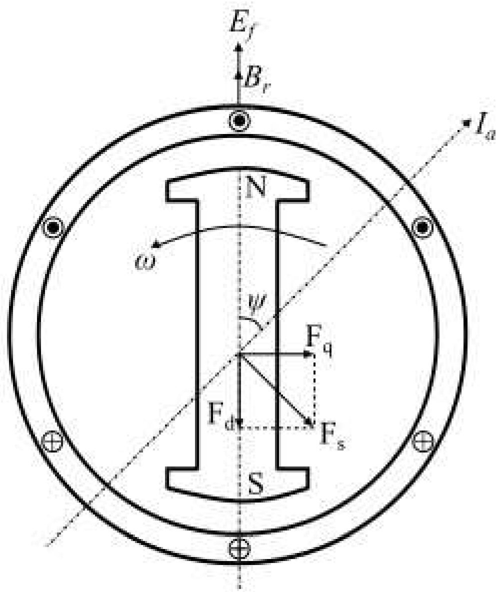


Figure-2

Two Reaction Theory of Salient Pole Machine

- 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

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

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

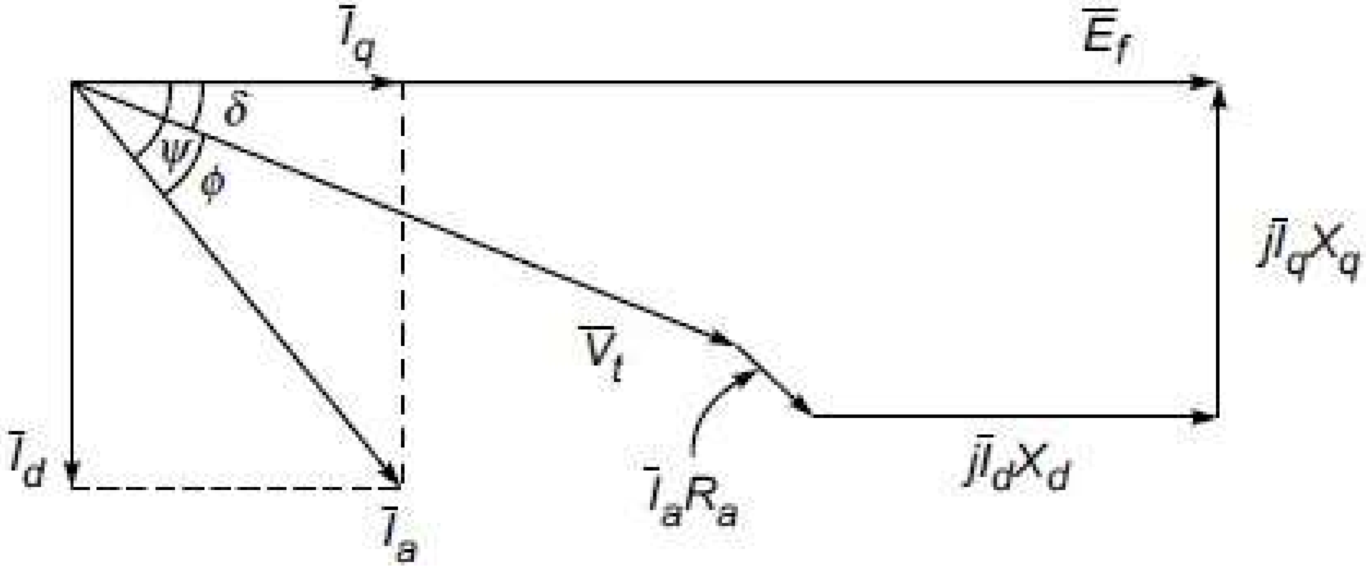
If we include the armature leakage reactance Xl which is the same on both axes, we get: Direct axis synchronous reactance $X_d = X_{ad} + Xl$

and Quadrature axis synchronous reactance $Xq = Xaq + Xl$

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

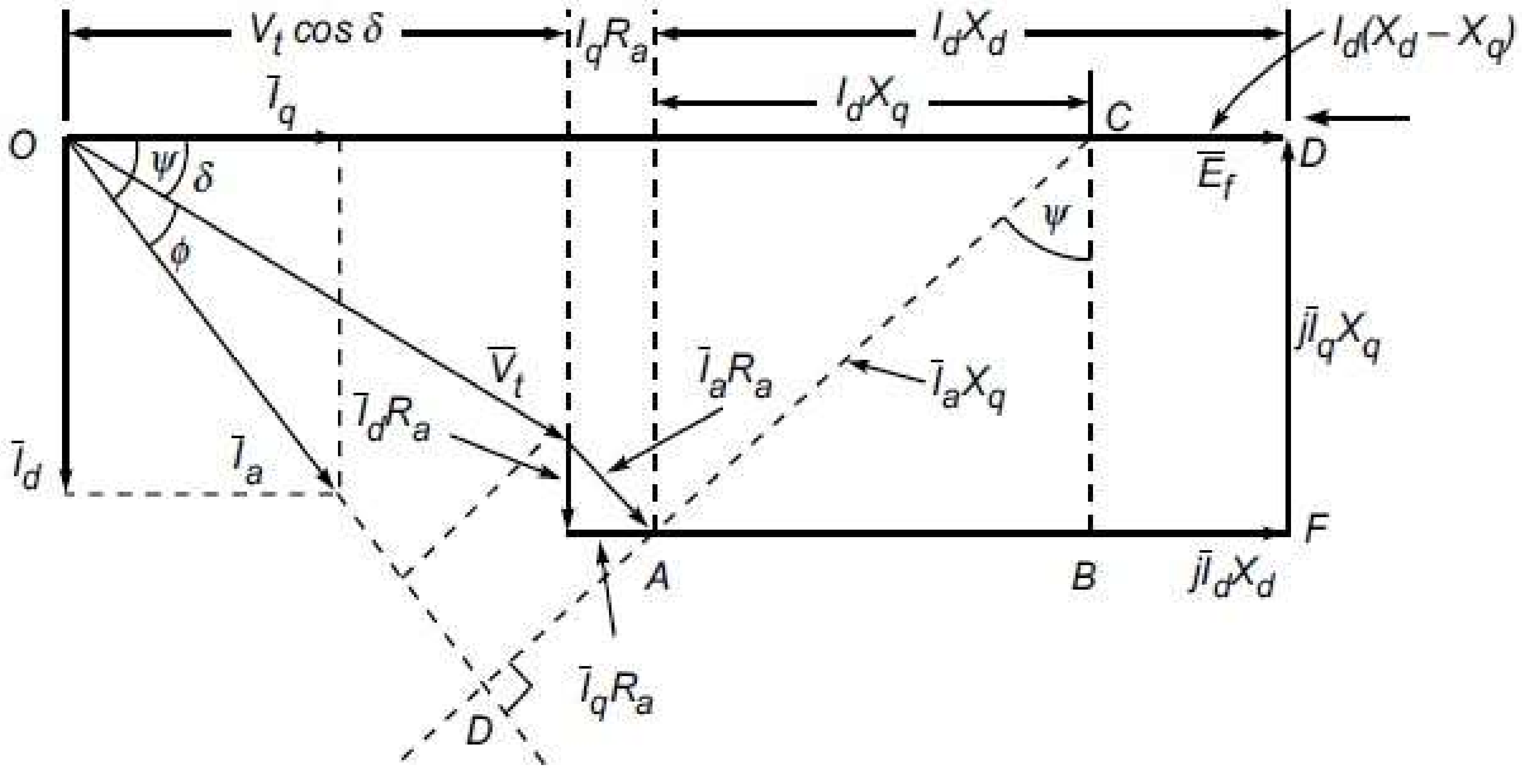
$$X_{aq} < X_{ad} \text{ or } X_q < X_d \text{ or } X_d > X_q$$

Phasor Diagram of Salient Pole Machine



- Armature current I_a is resolved into two components i.e. I_d and I_q
- Currents I_d and I_q causes voltage drops $jI_d X_d$ and $jI_q X_q$
- $jI_d X_d$ and $jI_q X_q$ leads I_d and I_q by 90^0
- Armature resistance drop Ia Ra is drawn parallel to Ia
- Vector for the drop IdXd is drawn perpendicular to Id whereas that for IqXq is drawn perpendicular to Iq. (Id = Ia sin ψ ; Iq = Ia cos ψ)
- $E0 = V + IaRa + jId\ Xd + jIq\ Xq$
- The angle $\Psi = \varphi + \delta$ is not known for a given Vt, Ia and φ.
- I_d and I_q cannot be found which are needed to draw the phasor diagram.

Calculation for Phasor Diagram



AC is drawn at 90° to the current phasor Ia and CB is drawn at 90° to Ef .

In Δ ODC: ∟OCD=90^0- ψ, ∟OCB=90^0, ∟OCB=90^0 , ∟ACB=90^0-(90^0- ψ)= ψ

Id = Ia sin ψ ; Iq = Ia cos ψ ; hence, Ia = Iq/cos ψ, IaRa cos ψ =IqRa

In Δ ABC: $\cos\psi = \frac{BC}{AC} = \frac{I_qX_q}{AC}$ $AC = \frac{I_qX_q}{\cos\psi} = I_aX_q$ $AB = I_aX_q\sin\psi = I_dX_q$

$CD = BF = I_d(X_d - X_q)$

$$Ef = Vt\cos\delta + I_q R_a + I_dX_q + I_d(X_d - X_q) = Vt\cos\delta + I_q R_a + I_dX_d$$

A synchronous generator has Xd = 0.8 pu and Xq = 0.5 pu. It is supplying full-load at rated voltage at 0.8 lagging pf. Draw the phasor diagram and calculate the excitation emf. Also calculate power angle.
Repeat the problem by ignoring Xq and assuming Xs=Xd.

$\bar{V}_t = 1\angle 0°$ pu, $I_a = 1$ pu 0.8 lagging,

$\bar{I}_a = 1\angle -36.9°$ pu

$\bar{E}'_f = \bar{V}_t + j\bar{I}_a X_q$

$= 1 + j1\angle -36.9° \times 0.5 = 1 + 0.5\angle 53.1°$

$= 1.30 + j\,0.40 = 1.30\angle 17.1°$ pu

$\delta = 17.1°$

$\psi = \phi + \delta = 36.9° + 17.1° = 54°$

$I_d = I_a \sin\psi = 1 \times \sin 54° = 0.81$

$CD = I_d(X_d - X_q)$

$= 0.81\,(0.8 - 0.5) = 0.243$

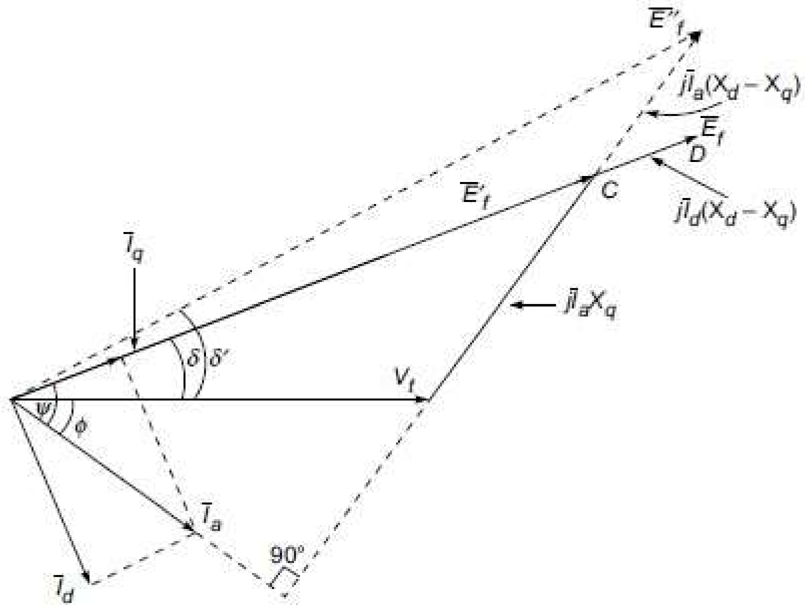
$\bar{E}_f = \bar{E}'_f + CD = 1.36 + 0.243 = 1.60$ pu

$\bar{E}''_f = \bar{V}_t + j\bar{I}_a X_d$

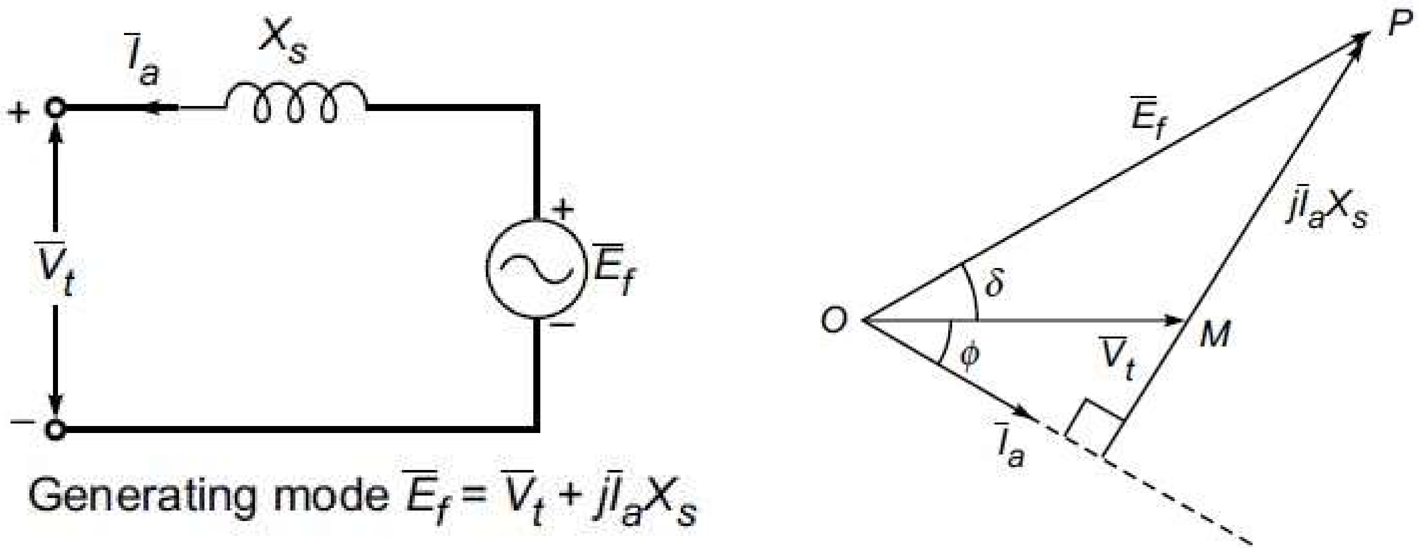
$= 1 + j\,1\angle -36.9° \times 0.8$

$= 1.48 + j\,0.64 = 1.61\angle 23.4°$

$E''_f = 1.61$ pu, $\delta' = 23.4°$



Power Angle Characteristics (P vs δ): Non-salient Pole



- Fig. above shows the circuit diagrams and phasor diagrams of a synchronous machine in generating mode
- The machine is connected to infinite bus-bars of voltage Vt.
- It is easily observed from the phasor diagrams that in generating mode, the excitation emf E_f leads V_t by angle δ.
- ∟OMP=180-(90-Φ)= 90+ Φ
- From the phasor triangle OMP: OP/(sin ∟OMP)= MP/(sin ∟MOP)

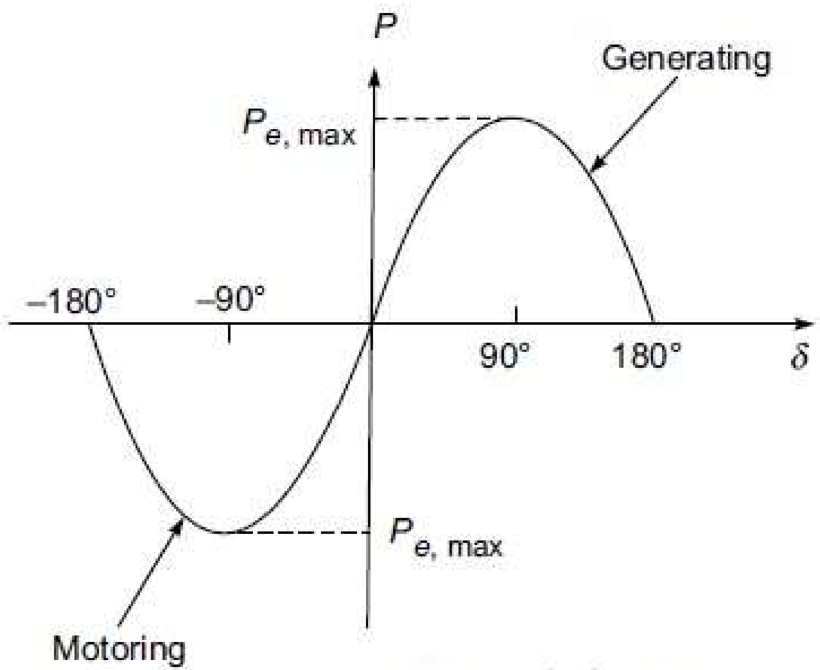
$$\frac{E_f}{\sin(90 \pm \phi)} = \frac{I_a X_s}{\sin \delta}; \quad \begin{matrix} (90^\circ + \phi), \text{ generating} \\ (90^\circ - \phi), \text{ motoring} \end{matrix} \qquad I_a \cos \phi = \frac{E_f}{X_s} \sin \delta$$

Power Angle Characteristics (P vs δ): Non-salient Pole

❖ Multiplying both sides by V_t :

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

$$P_e = \frac{V_t E_f}{X_s} \sin\delta$$



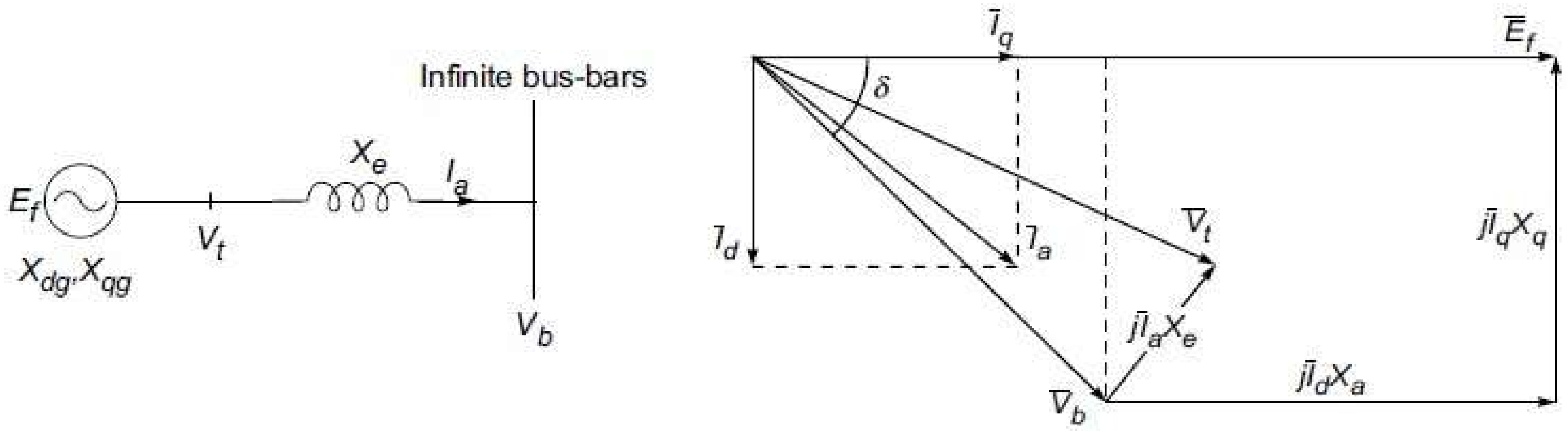
Power-angle characteristic

❖ $P_e = V_t I_a \cos\varphi$ = electrical power exchanged with the bus-bars

❖ δ = Angle between Ef and Vt and is called the power angle

❖ The relationship of Pe vs δ is known as the power-angle characteristic of the machine and is plotted for given V_t and E_f.

Power Angle Characteristics (P vs δ): Salient Pole



- Fig. above shows the one-line diagram of a salient pole synchronous machine connected to infinite bus bar of voltage Vb through a line of series reactance Xe.
- The total d- and q-axis reactance are: Xd = Xdg + Xe & Xq = Xqg + Xe
- From phasor diagram

$$P_e = I_d V_b \sin\delta + I_q V_b \cos\delta$$

$$I_d = \frac{E_f - V_b\cos\delta}{X_d}$$

$$I_q = \frac{V_b \sin\delta}{X_q}$$

Power Angle Characteristics (P vs δ): Salient Pole

$$P_e = \frac{E_f V_b}{X_d} \sin\delta + \underbrace{V_b^2 \frac{X_d - X_q}{2 X_d X_q} \sin 2\delta}_{\text{Reluctance power}}$$

✓The second term in above Eq. is known as the reluctance power.
✓The reluctance power varies as sin 2 δ with a maximum value at δ = 45° .
✓This term is independent of field excitation and would be present even if the field is unexcited