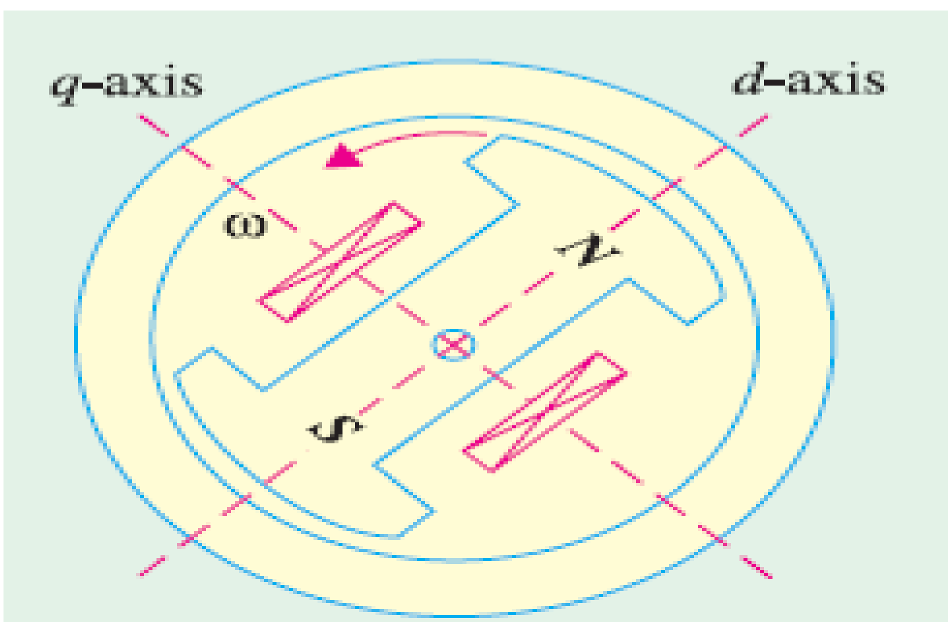
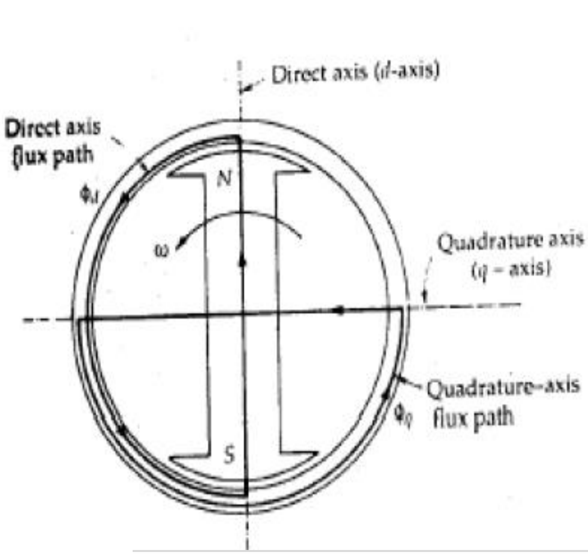
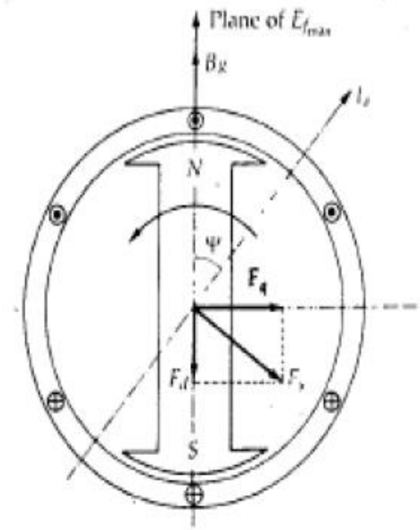
The Salient Pole Synchronous Machine

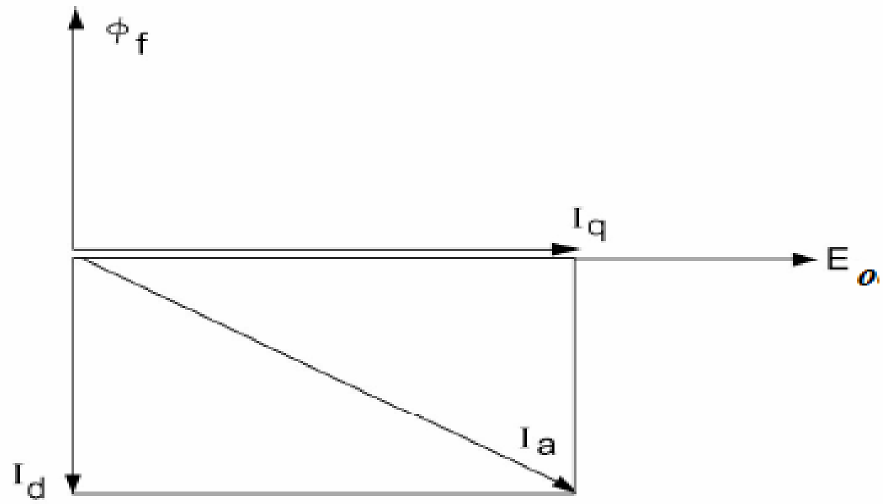
It is known that in case of cylindrical type synchronous machine the air gap is uniform. Due to uniform air gap, the field flux as well as armature flux vary sinusoidally in the air gap, the air gap length is constant and reactance is also constant. Due to this the mmf of armature and field act upon the same magnetic circuit all the time hence can be added vectorially.
But in salient pole type alternators the length of the air gap varies and the reluctance also varies. Hence the armature flux and field flux cannot vary sinusoidally in the air gap. The reluctance of the magnet circuits on which mmf act are different in case of salient pole alternators. Hence the armature and field mmf cannot be treated in a simple as they can be in cylindrical pole alternators. ***Salient-pole generators, such as hydroelectric generators, have armature inductances that are a function of rotor position, making analysis one step more complicated. The key to analysis of such machines is to separate mmf and flux into two orthogonal components. The two components are aligned with the direct axis and the quadrature axis of the machine. The direct axis is aligned with the field winding, while the quadrature axis leads the direct by 90°.***

Field poles in a salient-pole machine cause non uniformity of the magnetic reluctance of the air gap. The reluctance along the polar axis is appreciably less than that along the inter polar axis. We often refer to the polar axis as the direct axis and the inter polar as the quadrature axis. This effect can be taken into account by resolving the armature current I_a into two components,
one in time phase and the other in time quadrature with the excitation voltage as shown in Fig. The component I_d of the armature current is along the direct axis (the axis of the field poles), and the component I_q is along the quadrature axis. Let us consider the effect of the direct-axis component alone. With I_d lagging the excitation EMF E_f by 90°, the resulting armature-reaction flux φ_{ad} is directly opposite the filed poles as shown in Fig. The effect of the quadrature axis component is to produce an armature-reaction flux φ_{aq}, which is in the quadrature-axis direction as shown in Figure.

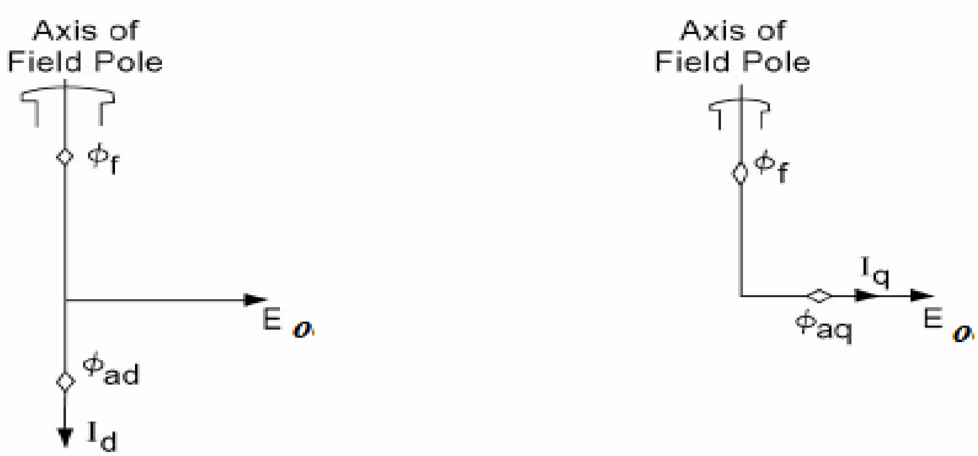








Resolution of Armature Current in Two Components.



Direct-Axis and Quadrature-Axis Air-Gap Fluxes in a Salient-Pole Synchronous

21.1 Two Reaction Theory:

The theory which gives the method of analysis of the disturbing effects caused by salient pole construction is called Two Reaction Theory. Professor Andre Blonded has put forward the two reaction theory.

According to this theory the armature mmf can be divided into two components as;

1. ***Component acting along the pole axis called direct axis d-axis.***
2. ***Components acting at right angles to the pole axis called quadrature axis q-axis.***

The component acting along direct axis can be magnetizing or demagnetizing. The component acting along quadrature axis is cross magnetizing. These components produce the effect of different kinds.

According to two reaction theory:

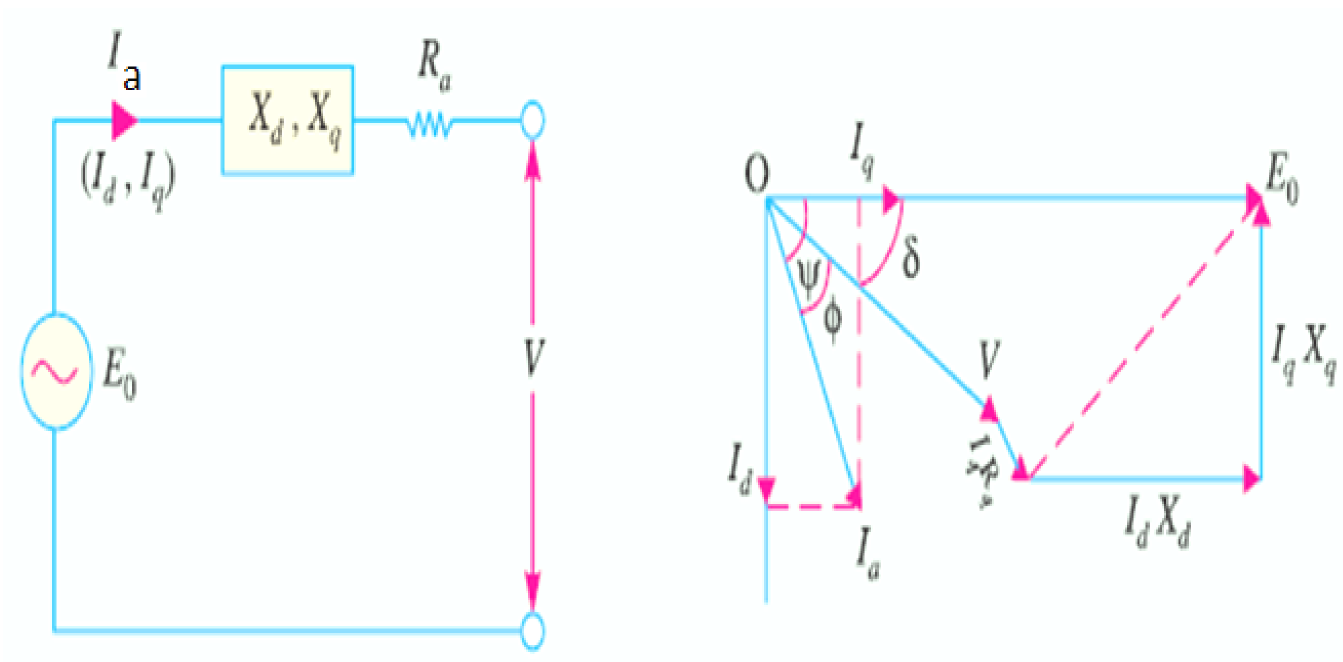
- ***i- The armature current*** I_a ***may be resolved into two components*** I_d ***perpendicular to*** E_o ***&*** I_q ***along*** E_o.
- ***ii- The armature reactance has two components; d-axis armature reactance*** X_{ad} ***linked with*** I_d ***and q-axis armature reactance*** X_{aq} ***linked with*** I_q.

By adding the armature leakage reactance X_{la} ***with each*** X_{ad} ***and*** X_{aq}.

$$X_d = X_{ad} + X_{la}$$
$$X_q = X_{aq} + X_{la}$$

The reluctance along q – axis is larger than that of d – axis due to larger air gap.

$$X_{ad} \rangle X_{aq} \qquad Then \quad X_d \rangle X_q$$



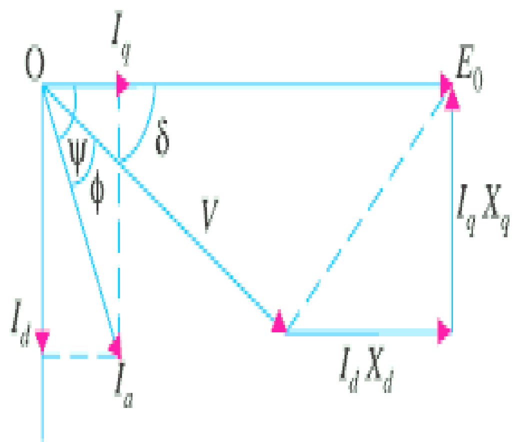
δ=The power angle or load angle, between V & E_o
ψ= Internal power factor angle, between I_a &E_o.

$$E_o = V + I_a R_a + jI_d X_d + jI_q X_q$$

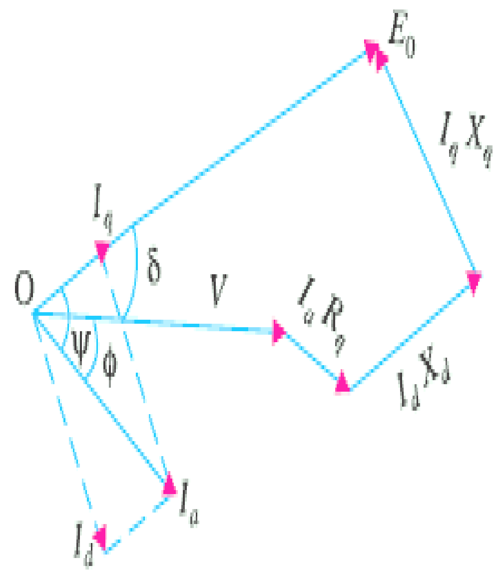
$$I_a = I_d + j\ I_q$$

Neglecting R_a

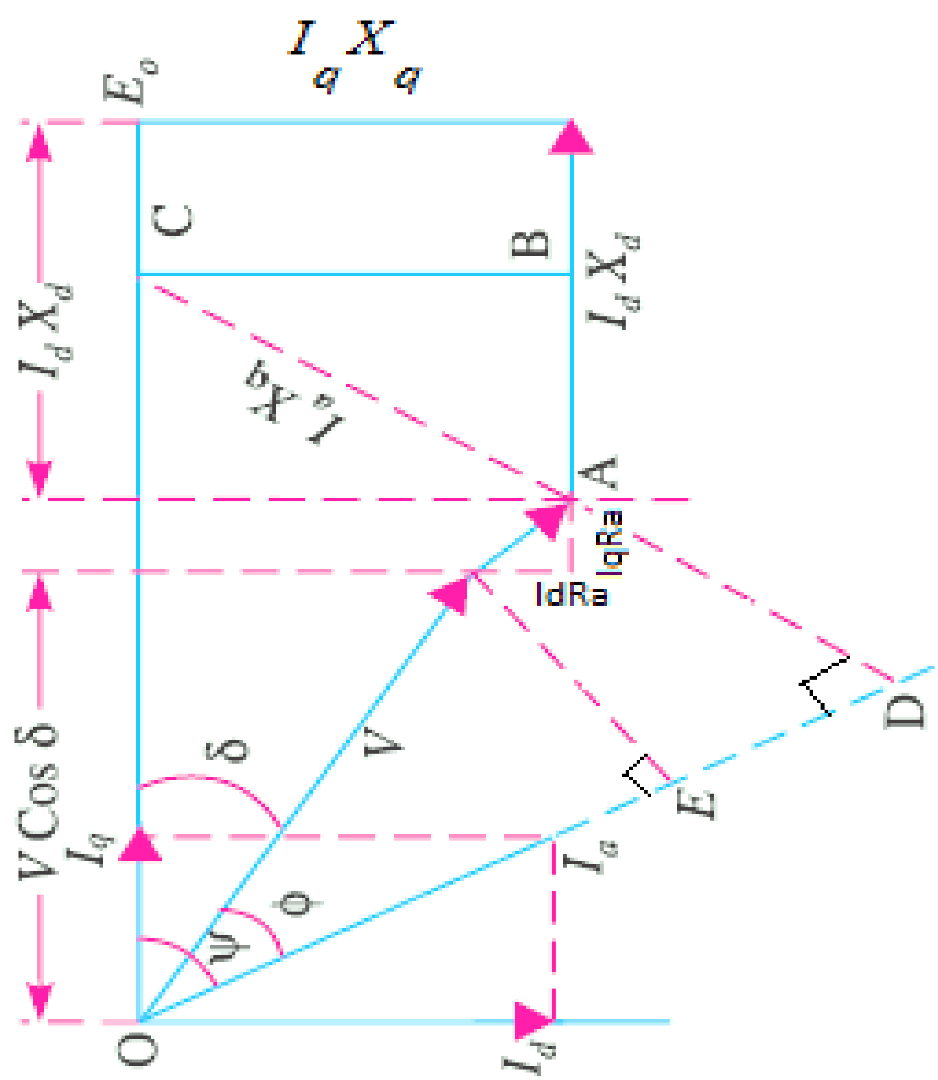
$$E_o = V + jI_d X_d + jI_q X_q$$


O
I_q
E_0
δ
ψ
φ
V
I_q X_q
I_d
I_a
I_d X_d

(a)


E_0
I_q X_q
I_q
δ
O
V
I_a R_a
ψ
φ
I_d X_d
I_a
I_d

(b)


I_q X_q
E_o
C
B
I_d X_d
I_d X_d
I_a X_q
A
IqRa
IdRa
D
E
V Cos δ
I_q
δ
V
ψ
φ
I_a
O
I_d

$$I_d = I_a \sin\psi$$

$$I_q = I_a \cos\psi, \ hence \ I_a = \frac{I_q}{\cos\psi}$$

$$In \ \Delta ABC \ , \frac{BC}{AC} = \cos\psi \ or \ AC = \frac{BC}{\cos\psi} = I_a X_q$$

$$From \ \Delta ODC, \ we\,get \ \tan\psi = \frac{AD + AC}{OE + ED}$$

$$= \frac{V\sin\phi + I_a X_q}{V\cos\phi + I_a R_a} \quad (generating \ \text{mode})$$

$$= \frac{V\sin\phi - I_a X_q}{V\cos\phi - I_a R_a} \quad (motoring \ \text{mode})$$

$$\delta = \psi - \phi \ \ (generating) \ \& \ \delta = \phi - \psi \ (motoring)$$

$$E_o = V\cos\delta + I_q R_a + I_d X_d \qquad Generating$$

$$E_o = V\cos\delta - I_q R_a - I_d X_d \qquad Motoring$$

$$I_d = I_a \sin\psi = I_a \sin(\phi \pm \delta) \ \&$$

$$I_q = I_a \cos\psi = I_a \cos(\phi \pm \delta)$$

$$V\sin\delta = I_q X_q = I_a X_q \cos(\phi \pm \delta)$$

$$= I_a X_q (\cos\phi\cos\delta \pm \sin\phi\sin\delta) \ dividing \ \sin\delta$$

$$Then \quad V = I_a X_q \cos\phi\cot\delta \pm I_a X_q \sin\phi$$

$$\tan\delta = \frac{I_a X_q \cos\phi}{V \pm I_a X_q \sin\phi}$$

$+$ *for synchronous generator*

$-$ *for synchronous motor*

21.2 The Salient Pole Synchronous Machine Advantages:

1- The presence of large air gap in inter polar region gives better ventilation.
2- It develops more power for same excitation.
3- For same power developed and with same excitation, the load angle is less if its compared with cylindrical type.
4- The salient pole machine develops reluctance power which is help the machine to continuous to operate on infinite bus bars even if the excitation fails.
5- With larger ($dP_d/d\delta$), salient pole machine can withstand more fluctuating loads.

21.2 The Power Developed by a synchronous Generator:

Neglecting the armature resistance(cu-loss), then:

$$P_{out} = VI_a \cos\phi = The\ \ power\ \ developed\ P_d \qquad (1)$$

$$V \sin\delta = I_q X_q \ \ ,\ \ E_o - V\cos\delta = I_d X_d \qquad (2)$$

$$I_d = I_a \sin(\phi + \delta), I_q = I_a \cos(\phi + \delta) \qquad (3)$$

$$Substituting\ \ \ eq.\ 3\ \ in\ \ eq.\ 2\ \ and\ \ solving\ \ I_a \cos\phi$$

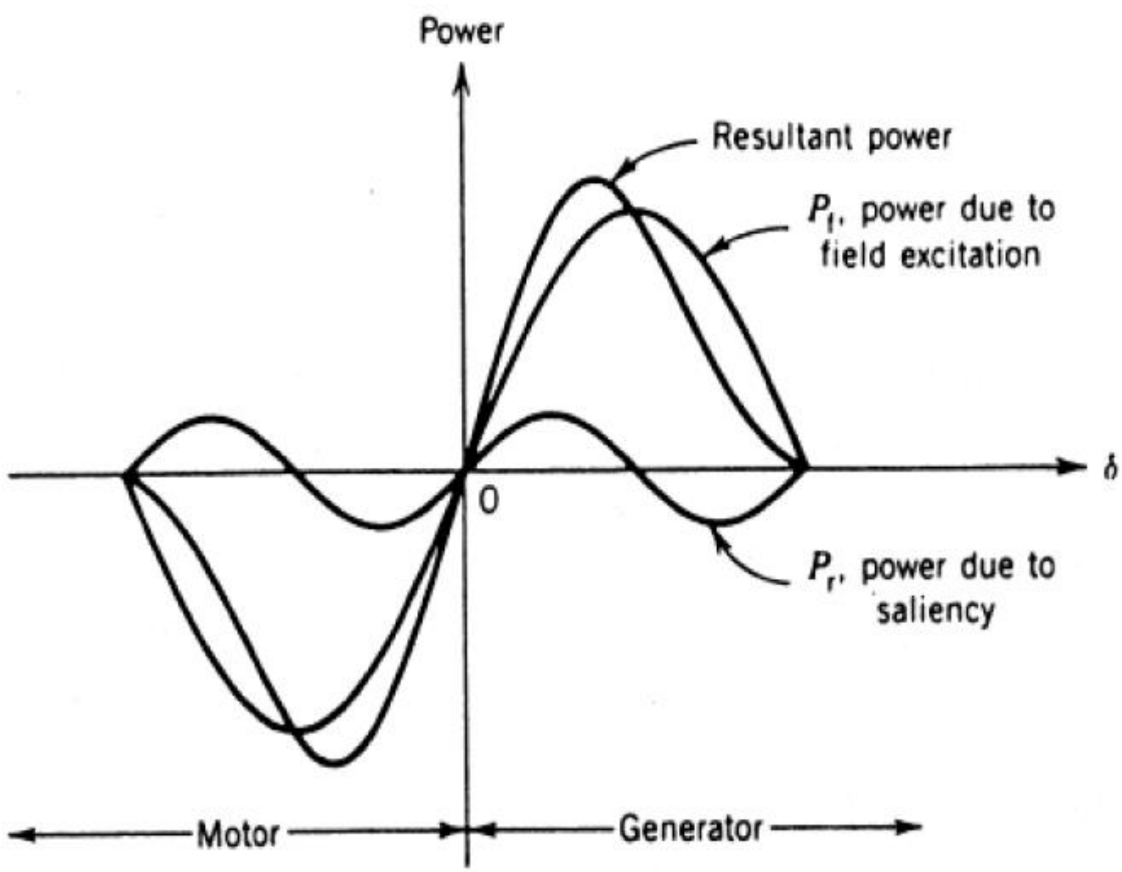
$$I_a \cos\phi = \frac{E_o}{X_d}\sin\delta + \frac{V}{2}\left(\frac{1}{X_q} - \frac{1}{X_d}\right)\sin 2\delta$$

$$The\ \ toatal\ \ power\ \ for\ \ three\ \ phase$$

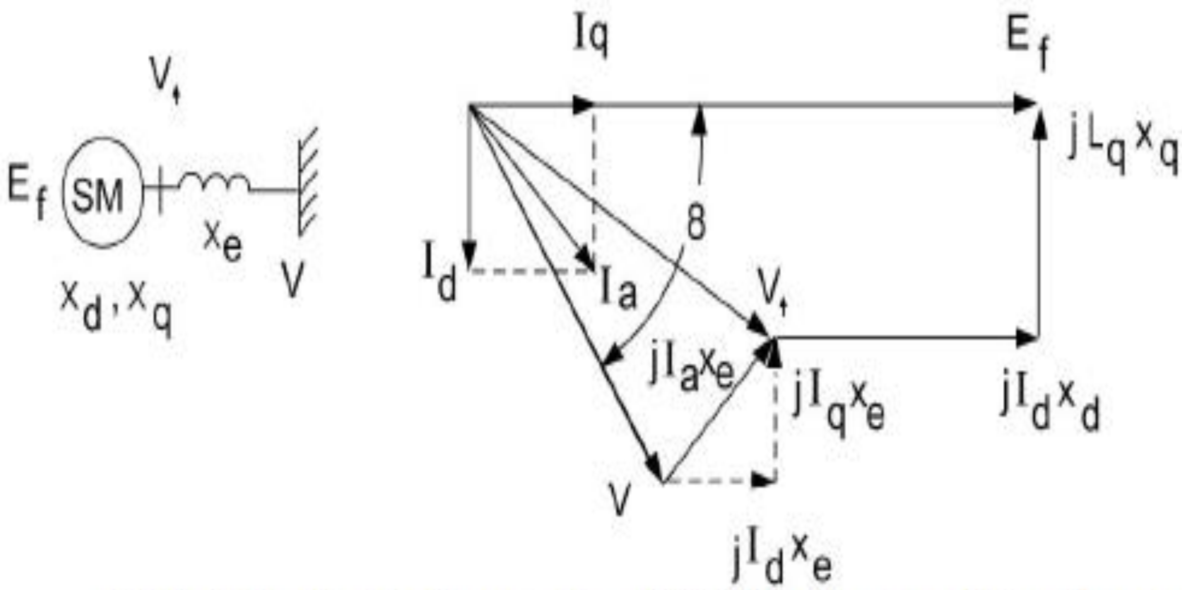
$$\therefore P_{out} = P_d = \frac{3E_oV}{X_d}\sin\delta + \frac{3V^2}{2}\left(\frac{1}{X_q} - \frac{1}{X_d}\right)\sin 2\delta$$

The power developed consists of two components,

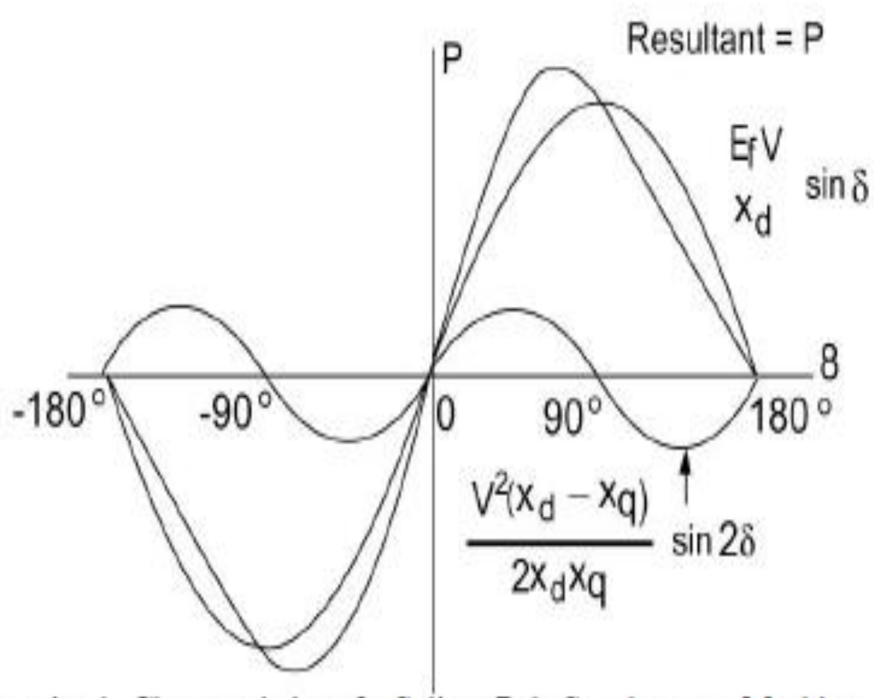
- ***the first term represents power due to field excitation***
- ***The second term gives the reluctance power(power due to saliency). If X_d=X_q, the machine has a cylindrical rotor, the second term becomes zero and the power is given by the first term only.***
- ***If the field current is zero, then E_o=0, then the first term is zero and the power developed by the second term.***



Power–angle characteristic of a salient pole synchronous machine.



A Salient-Pole Machine Connected to an Infinite Bus through an External Impedance.



Power Angle Characteristics of a Salient-Pole Synchronous Machine.

Example 1; *A 3-phase, Y-connected syn. generator supplies current of 10 A having phase angle of 20° lagging at 400 V. Find the load angle and the components of armature current I_d and I_q if X_d = 10 ohm and X_q = 6.5 ohm. Assume arm. resistance to be negligible.*

Solution.

$$\cos\phi = \cos 20° = 0.94;\ \sin\phi = 0.342;\ I_a = 10\ \text{A}$$

$$\tan\delta = \frac{I_a X_q \cos\phi}{V + I_a X_q \sin\phi} = \frac{10\times 6.5\times 0.94}{400 + 10\times 6.5\times 0.342} = 0.1447$$

$$\delta = 8.23°$$

$$I_d = I_a \sin(\phi+\delta) = 10\sin(20° + 8.23°) = 4.73\ \text{A}$$

$$I_q = I_a \cos(\phi+\delta) = 10\cos(20° + 8.23°) = 8.81\ \text{A}$$

Incidentally, if required, voltage regulation of the above generator can be found as under:

$$I_d X_d = 4.73\times 10 = 47.3\ \text{V}$$

$$E_0 = V\cos\delta + I_d X_d = 400\cos 8.23° + 47.3 = 443\ \text{V}$$

$$\%\ \text{regn.} = \frac{E_0 - V}{V}\times 100$$

$$= \frac{443-400}{400}\times 100 = 10.75\%$$

Note: The 400V for the above example is phase voltage.

Example 2: *A 3-phase synchronous generator is delivering a power of 0.9 infinite bus at rated voltage and at pf 0.8 lagging. The generator has $X_d = 1.0$ $X_q = 0.6$ p.u. Determine the load angle and the excitation voltage.*

In case loss of excitation takes place, will the generator remain in synchronism ?

Solution. In per unit system,

$$V_t I_a \cos\theta = \text{Power}$$

or $$1 \times I_a \times 0.8 = 0.9$$

$\therefore$ $$I_a = 1.125 \text{ p.u.}$$

It is seen from the phasor diagram of Fig.

with $r_a = 0$ that $$\tan(\delta + \theta) = \frac{I_a X_q + V_t \sin\theta}{V_t \cos\theta} = \frac{1.125 \times 0.6 + 1 \times 0.6}{1 \times 0.8}$$

or $$(\delta + \theta) = 57.894°$$

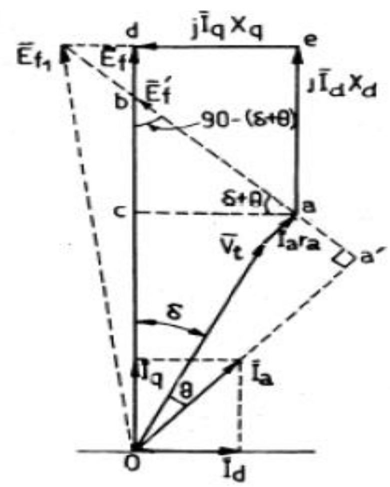
$\therefore$ $$\delta = 57.894° - \cos^{-1}(0.8) = 57.894° - 36.87° = 21.024°.$$

Also $$I_d = I_a \sin(\delta + \theta) = 1.125 \sin(57.894°) = 0.953 \text{ p.u.}$$

$\therefore$ $$E_f = V_t \cos\delta + I_d X_d = 1 \times \cos 21.024° + 0.953 \times 1.0 = 1.8864 \text{ p.u.}$$

When loss of excitation takes place, $E_f = 0$ and the maximum power is then given by

$$\frac{1}{2} V_t^2 \left(\frac{1}{X_q} - \frac{1}{X_d}\right) \sin 2\delta$$



$$= \frac{1}{2}\left(\frac{1}{0.6} - \frac{1}{1}\right) \sin 90° = 0.333 \text{ p.u.}$$

loss of excitation, the maximum power that the reluctance generator can deliver to bus is 0.333 p.u. As this is less than 0.9 p.u., the generator will lose synchronism.

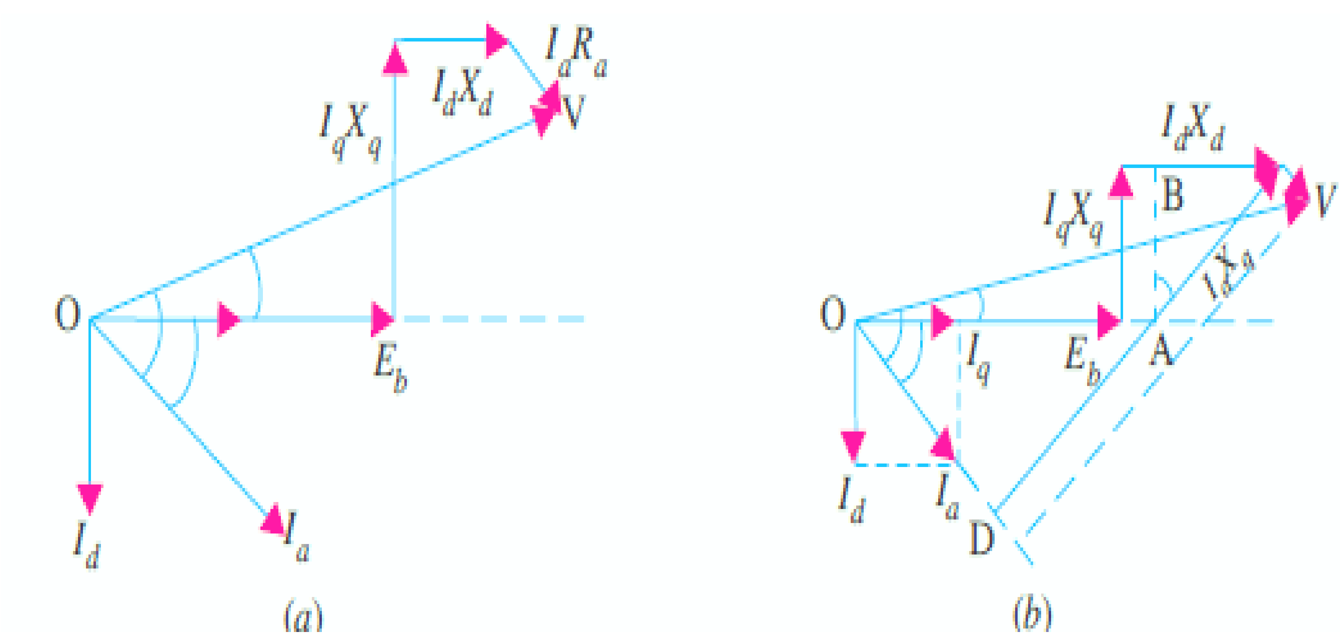
21.3 The Power Developed by a synchronous Motor:

The expression for the power developed by a salient pole synchronous motor:

The total mechanical power for three phase synchronous motor

$$\therefore P_m = \frac{3E_oV}{X_d}\sin\delta + \frac{3V^2}{2}\left(\frac{1}{X_q} - \frac{1}{X_d}\right)\sin 2\delta$$

$$T_e = \frac{3E_oV}{\omega_s X_d}\sin\delta + \frac{3V^2}{2\omega_s}\left(\frac{1}{X_q} - \frac{1}{X_d}\right)\sin 2\delta$$



Depending on the phasor diagram

$$\tan\psi = \frac{V\sin\phi - I_q X_q}{V\cos\phi - I_a R_a}$$

Neglecting R_a

$$\tan\psi = \frac{V\sin\phi - I_q X_q}{V\cos\phi}$$

$$\delta = \phi - \psi$$

$$E_o = V\cos\delta - I_q R_a - I_d X_d$$

$$\tan\delta = \frac{I_a X_q \cos\phi}{V - I_a X_q \sin\phi}$$

If R_a *included then*

$$\tan\delta = \frac{I_a X_q \cos\phi - I_a R_a \sin\phi}{V - I_a X_q \sin\phi - I_a R_a \cos\delta}$$

Example 3:

A 400V, three phase, Y-connected synchronous motor with X_d=6Ω 7& X_q=4 Ω is running in parallel with infinite bus bar. If the field current is reduced to zero, find the maximum load that can be put on synchronous motor& the armature current at maximum power (neglect armature cu losses).

Solution:

$$I_f = 0 \Rightarrow E_b = 0$$

$$P = \frac{1}{2}V^2\left(\frac{1}{X_q} - \frac{1}{X_d}\right)\sin 2\alpha$$

for maximum reluctance power 2α must be equal to 90^0

$$\alpha = 45^0$$

$$P_{\max} = \frac{1}{2}(400/\sqrt{3})^2\left(\frac{1}{4} - \frac{1}{6}\right) = 6660\,Watt$$

$$I_q = \frac{V\sin\alpha}{X_q} = \frac{400/\sqrt{3}\times\sin 45}{4} = 40.82A$$

$$I_d = \frac{V\cos\alpha}{X_d} = \frac{400/\sqrt{3}\times\cos 45}{6} 27.2A$$

$$I_a = \sqrt{I_d{}^2 + I_q{}^2} = \sqrt{27.2^2 + 40.82^2} = 49.061A$$

Example 4; *A 3-ϕ, 150-kW, 2300-V, 50-Hz, 1000-rpm salient-pole synchronous motor has X_d = 32 Ω / phase and X_q = 20 Ω / phase. Neglecting losses, calculate the torque developed by the motor if field excitation is so adjusted as to make the back e.m.f. twice the applied voltage and α = 16°.*

Solution. $V = 2300/\sqrt{3} = 1328$ V ; $E_b = 2 \times 1328 = 2656$ V

Excitation power / phase $= \frac{E_b V}{X_d}\sin\alpha = \frac{2656\times 1328}{32}\sin 16° = 30{,}382$ W

Reluctance power / phase $= \frac{V^2(X_d - X_q)}{2X_d X_q}\sin 2\alpha = \frac{1328^2(32-20)}{2\times 32\times 20}\sin 32° = 8760$ W

Total power developed, $P_m = 3(30382 + 8760) = 117,425$ W

$T_g = 9.55 \times 117{,}425/1000 =$ **1120 N-m**

Example 5: A 3.3kV, 1.5MW, three phase synchronous motor has X_d=4Ω and Xq=3Ω per phase. Neglecting all loss, calculate the maximum mechanical power for this excitation.

Solution:

$$V = 3300/\sqrt{3} = 1905V, \qquad \cos\phi = 1 \ \&$$

$$\sin\varphi = 0, \ \phi = 0$$

$$I_a = \frac{1500000}{\sqrt{3}\times 3300\times 1} = 262A$$

$$\tan\psi = \frac{V\sin\phi - I_a X_q}{V\cos\phi} = \frac{1905\times 0 - 262\times 3}{1905} = -0.4125,$$

$$\therefore \psi = -22.4^0$$

$$I_d = 262\sin - 22.4) = -100A$$

$$I_q = 262\cos(-22.4) = 242A$$

$$E_0 = V\cos\delta - I_d X_d = 1905\cos(-22.4) - (-100\times 4) = 2160V$$

$$P_m = \frac{3E_oV}{X_d}\sin\delta + \frac{3V^2}{2}\left(\frac{1}{X_q} - \frac{1}{X_d}\right)\sin 2\delta$$

$$P_m = \frac{3\times 2160\times 1905}{4}\sin\delta + \frac{3\times 1905^2}{2}\left(\frac{1}{3} - \frac{1}{4}\right)\sin 2\delta$$

$$for\ developed \max\ power\ , \frac{dP_m}{d\delta} = 0$$

$$\frac{dP_m}{d\delta} = 0 = 1029\cos\delta = 2\times 151\times\cos 2\delta$$

$$\delta = 73.4^o, \ Substitute\ in\ the\ power\ equation\ then$$

$$\therefore P\max = 3210kWatt$$