EE-362 ELECTROMECHANICAL ENERGY CONVERSION-II

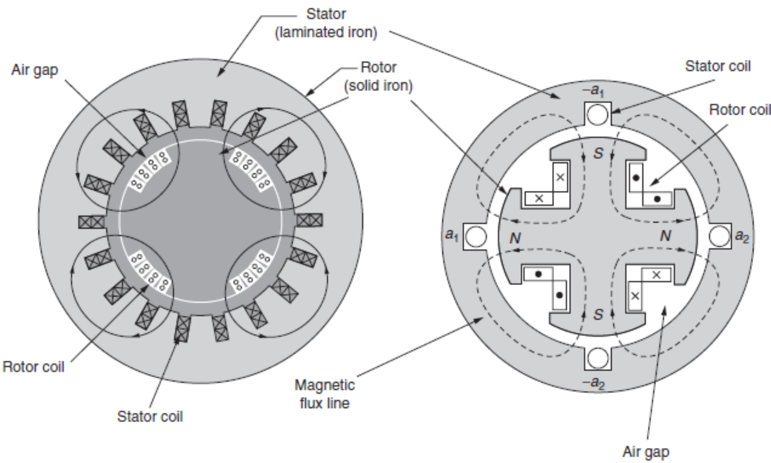
Salient Pole Synchronous Machines

Ozan Keysan

keysan.me

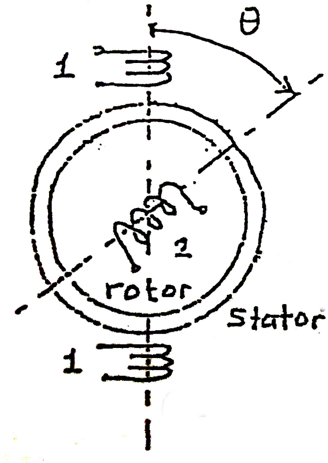
Office: C-113 • Tel: 210 7586

Cylindrical Machine vs. Salient Pole



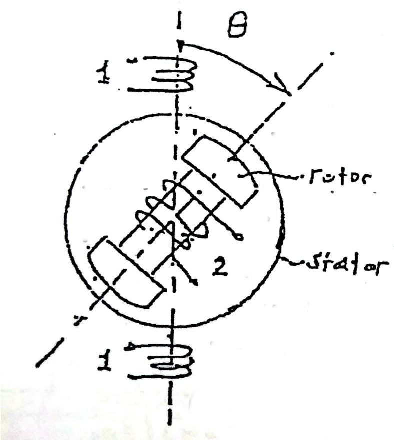
Salient Pole: Position dependent air-gap reluctance(and hence inductance; $L = N^2/R$)

Torque in Cylindrical Rotor, Cylindrical Stator



$$T = i_1 i_2 \frac{\partial M}{\partial \theta}$$

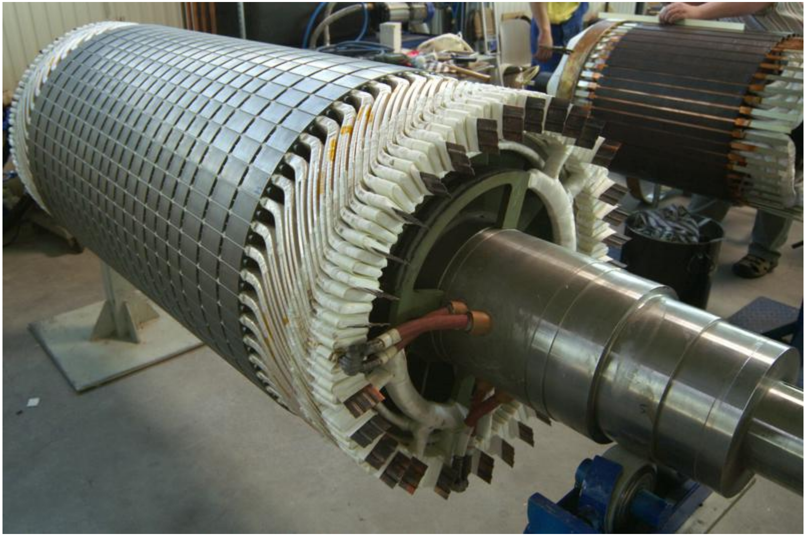
Torque in Salient Rotor, Cylindrical Stator



$$T = i_1 i_2 \frac{\partial M}{\partial \theta} + \frac{1}{2} i_1^2 \frac{\partial L_{11}}{\partial \theta}$$

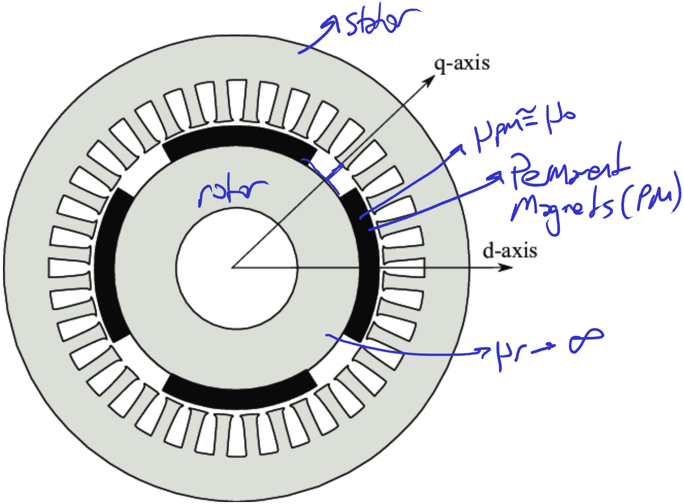
Cylindrical Rotor Synchronous Machine

No saliency in the rotor: no reluctance torque



SMPM: Surface Mount Permanent Magnet Motor

No saliency in the rotor: no reluctance torque



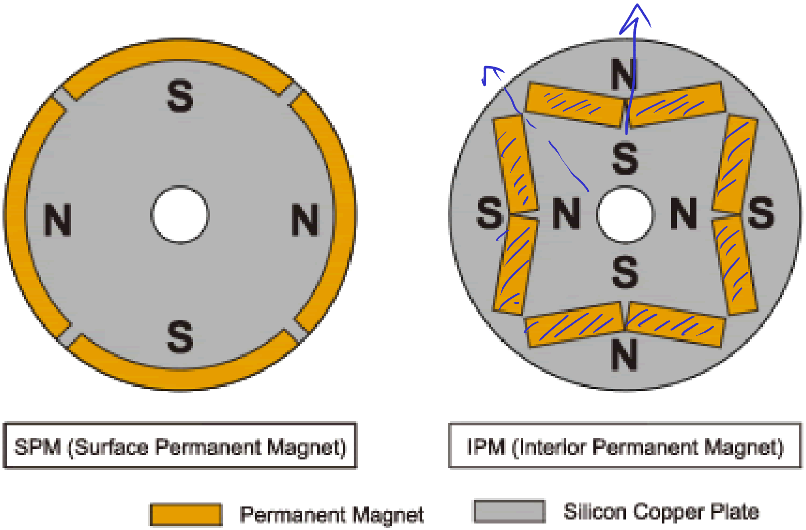
Salient Pole Rotor Synchronous Machines

Airgap is not uniform.

There are both reluctance and synchronous torque components

Motors With Saliency (has reluctance torque)

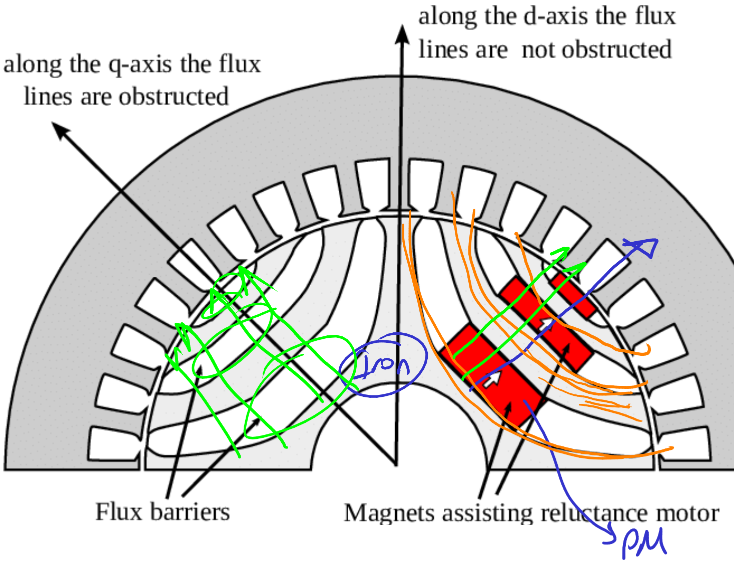
IPM: Interior Permanent Magnet Motor



Motors With Saliency (has reluctance torque)

SRM: Synchronous Reluctance Motor

(with or without PM)



Motors With Saliency (has reluctance torque)

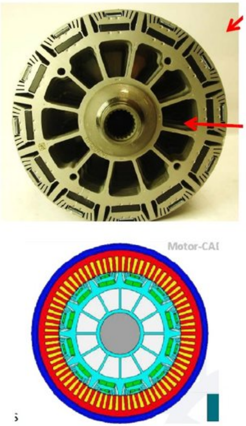
Most electric car motors have reluctance torque

A sampling of Internal Permanent Magnet (IPM) rotors. Image from Researchgate.net

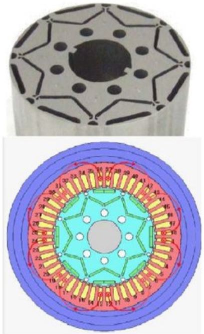
Motors With Saliency (has reluctance torque)

Most electric car motors have reluctance torque

BMW



Nissan



Bolt

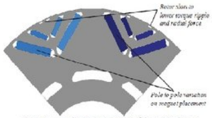
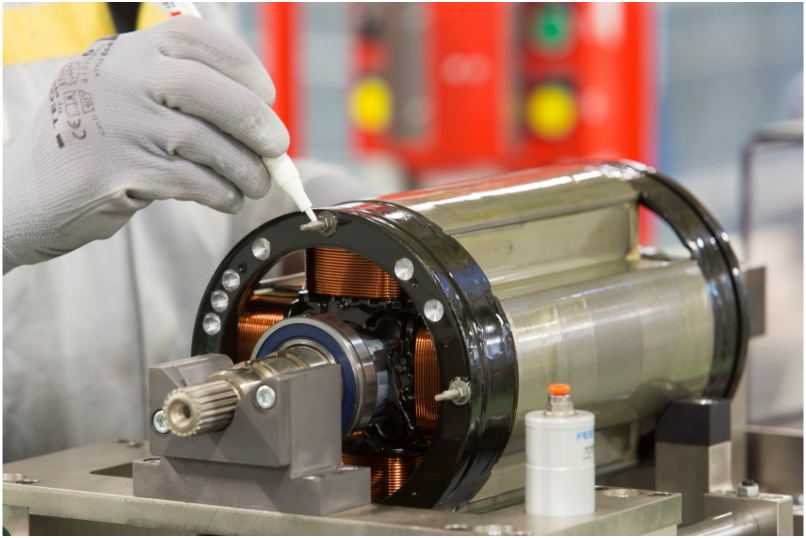


Figure 14. Rotor lamination geometry of the optimized rotor

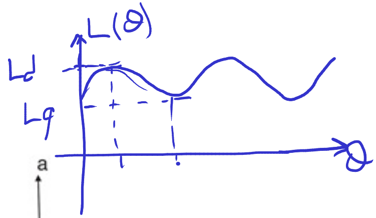
Model 3

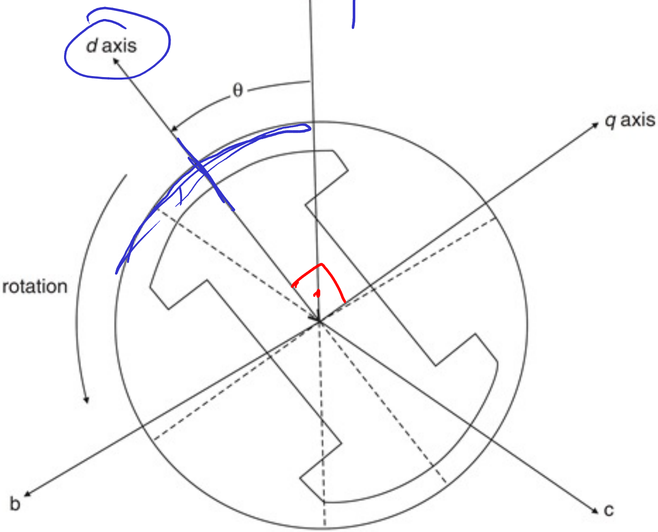
Salient Pole Synchronous Motor

Renault Zoe, 80kW motor



D-Q Axis



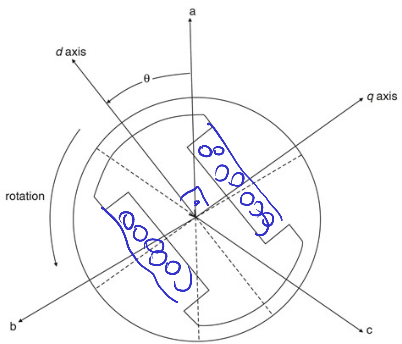


$L = N^2/R$

d-axis ⇒ Min. reluctance
↳ Inductance is max

q-axis ⇒ Max. reluctance
↳ Inductance is min.

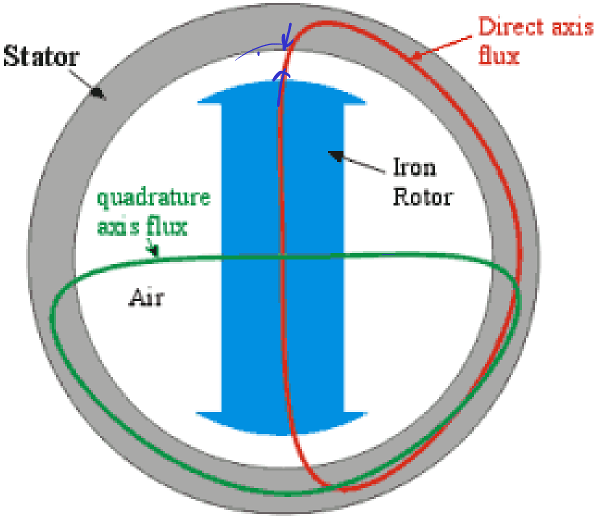
D-Q Axis

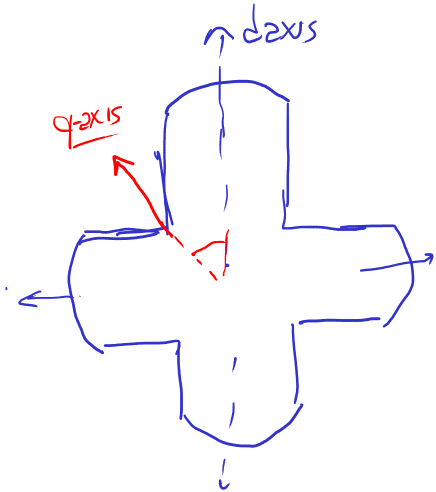


Direct Axis: d-axis

Quadrature Axis: q-axis

D-Q Axis





Remember reluctance torque

D-Q Axis

Salient Pole Machine:

$$L_d > L_q \rightarrow X_d > X_q$$

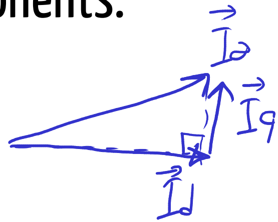
(Usually $X_q = 0.6 - 0.7\ X_d$)

Cylindrical Machine: $X_d = X_q = X_s$

Phasor Diagram in a Salient Pole Machine

Separate I_a in to two components:

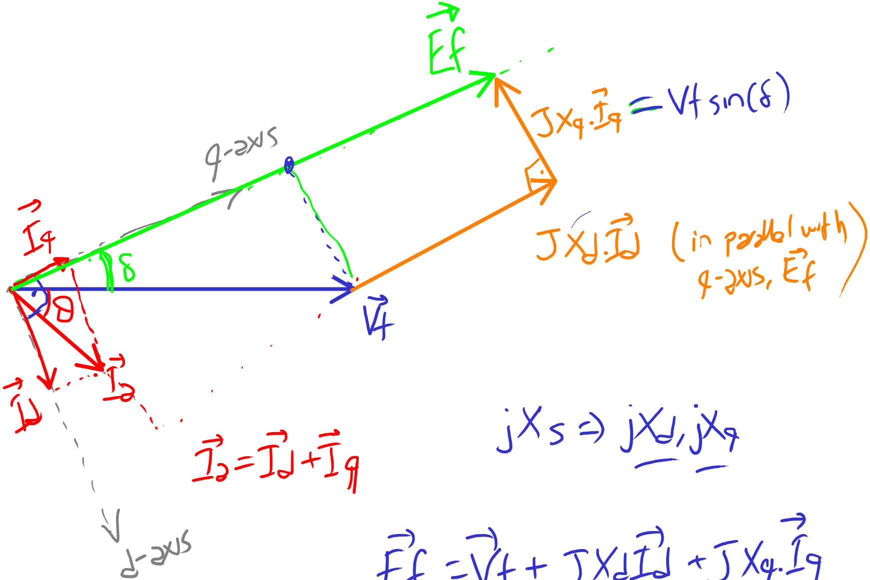
$$\overrightarrow{I_a} = \overrightarrow{I_d} + \overrightarrow{I_q}$$



- Direct-axis current I_d: In phase with ϕ_f
- Quadrature-axis current I_q: Perpendicular to ϕ_f, and therefore in-phase with E_f

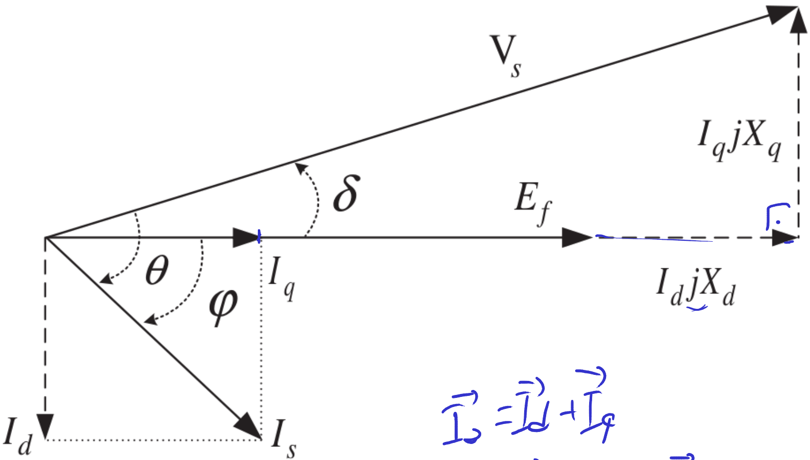
$E_f \propto \frac{d\phi_f}{dt}$ $\vec{I_q} \parallel \vec{E_f}$

Phasor Diagram in a Salient Pole Machine (Generating)



$$\vec{E_f} = \vec{V_f} + jX_d\vec{I_d} + jX_q.\vec{I_q}$$

Phasor Diagram in a Salient Pole Machine (Motoring)



$$\vec{I_s} = \vec{I_d} + \vec{I_q}$$

$$\vec{V_t} = \vec{E_f} + jX_d\vec{I_d} + jX_q\vec{I_q}$$

Phasor Diagram in a Salient Pole Machine

Some key points:

$$|E_f| = V_t cos(\delta) + \underline{X_d I_d}$$

I_d has more effect on E_f (creates field flux)

cylindrical SM => $E_f \propto I_f$ ← field current

Phasor Diagram in a Salient Pole Machine

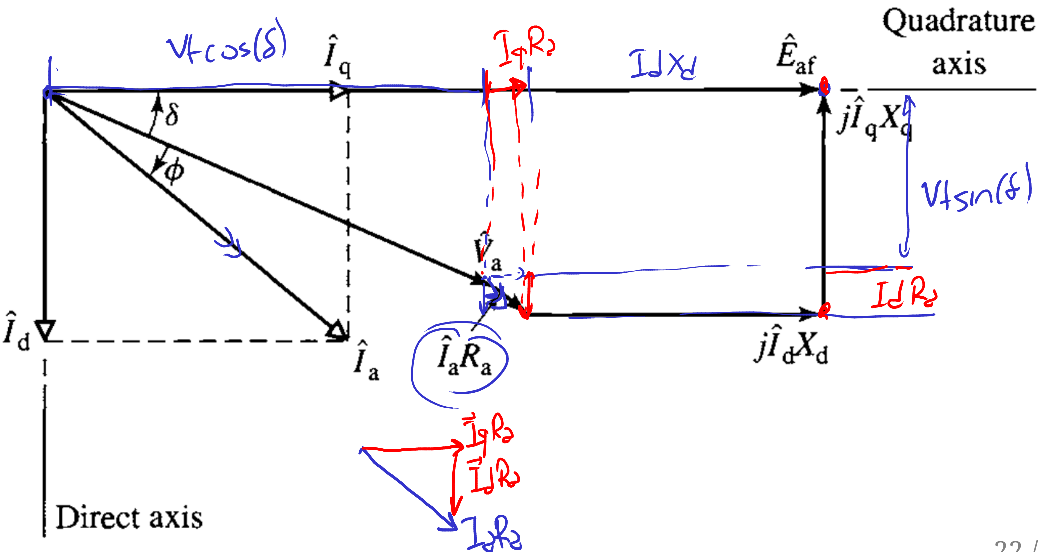
Some key points:

$$V_t sin(\delta) = X_q I_q$$

I_q has more effect on load angle δ (creates torque)

Phasor Diagram in a Salient Pole Machine

including R_a



Phasor Diagram in a Salient Pole Machine

including R_a

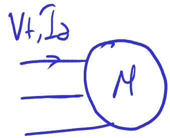
$$|E_f| = V_t cos(\delta) + X_d I_d + R_a I_q$$

$$V_t sin(\delta) + R_a I_d = X_q I_q$$

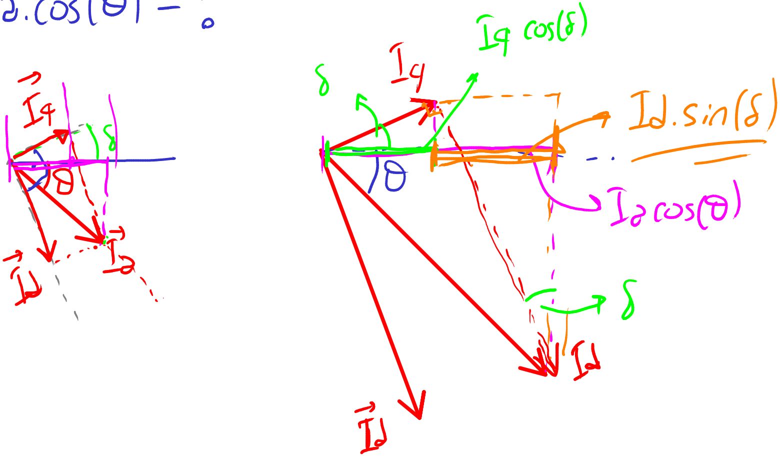
Power in Salient Pole Machines

Again the similar geometry tricks:

Start with: $P = 3V_t I_a cos(\theta)$



$I_a . cos(\theta) = ?$



$I_a cos(\theta)$

$= I_q . cos(\delta) + I_d sin(\delta)$

Power in Salient Pole Machines

Again the similar geometry tricks:

Start with: $P = 3V_tI_acos(\theta)$

$$I_acos(\theta) = I_dsin(\delta) + I_qcos(\delta)$$

Power in Salient Pole Machines

Again the similar geometry tricks:

Start with: $P = 3V_t I_a cos(\theta)$

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

$$P = 3V_t (I_d sin(\delta) + I_q cos(\delta))$$

Power in Salient Pole Machines

$$V_t sin(\delta) = X_q I_q$$

Power in Salient Pole Machines

$$V_t sin(\delta) = X_q I_q \rightarrow I_q = \frac{V_t sin(\delta)}{Xq}$$

Power in Salient Pole Machines

$$V_t sin(\delta) = X_q I_q \rightarrow I_q = \frac{V_t sin(\delta)}{Xq}$$

$$V_t cos(\delta) = E_f - X_d I_d$$

Power in Salient Pole Machines

$$V_t sin(\delta) = X_q I_q \rightarrow I_q = \frac{V_t sin(\delta)}{Xq}$$

$$V_t cos(\delta) = E_f - X_d I_d$$

$$\rightarrow I_d = \frac{E_f - V_t cos(\delta)}{X_d}$$

$$P = 3\left(V_t \cdot \left(\frac{E_f - V_t cos(\delta)}{X_d}\right) \cdot sin(\delta) + V_t \cdot \frac{V_t \cdot sin(\delta)}{X_q} \cdot cos(\delta)\right)$$

$$sin(a+b) = sin(a) \cdot sin(b) + cos(a) \cdot cos(b)$$

$a = b$

$$\hookrightarrow sin(2a) = 2\, sin(a) \cdot cos(b)$$

Power in Salient Pole Machines

$$P = 3\left(V_t\left(\frac{E_f - V_t\cos(\delta)}{X_d}\right).\sin(\delta) + V_t\,\frac{V_t.\sin(\delta)}{X_q}.\cos(\delta)\right)$$

$$\sin(a+b) = \sin(a).\sin(b) + \cos(a).\cos(b)$$

$a=b$

$$\hookrightarrow \sin(2a) = 2\sin(a).\cos(b)$$

$$P = 3\left[\frac{V_t.E_f.\sin(\delta)}{X_d} - \frac{V_t^2.\cos(\delta)\sin(\delta)}{X_d\,(X_q)} + \frac{V_t^2.\sin(\delta).\cos(\delta)}{X_q\,(X_d)}\right)$$

$$\sin(\delta).\cos(\delta) \hookrightarrow = \frac{\sin(2\delta)}{2}$$

$$P = 3\left[\frac{V_t.E_f.\sin(\delta)}{X_d} + \frac{V_t^2(X_d - X_q).\sin(2\delta)}{X_d X_q \quad 2}\right]$$

Power in Salient Pole Machines

Total Power:

$$P = 3\left[\frac{V_t E_f}{X_d} sin(\delta) + \frac{V_t^2 (X_d - X_q)}{2 X_d X_q} sin(2\delta)\right]$$

synchronous power

↳ reluctance power

If $X_d = X_q = X_s$ (cylindrical rotor)

$X_d > X_q \Rightarrow$ salient pole rotor

Power in Salient Pole Machines

Total Power:

$$P = 3\left[\frac{V_t E_f}{X_d} sin(\delta) + \frac{V_t^2 (X_d - X_q)}{2X_d X_q} sin(2\delta)\right]$$

- First Term: Same with Cylindrical Machines

Power in Salient Pole Machines

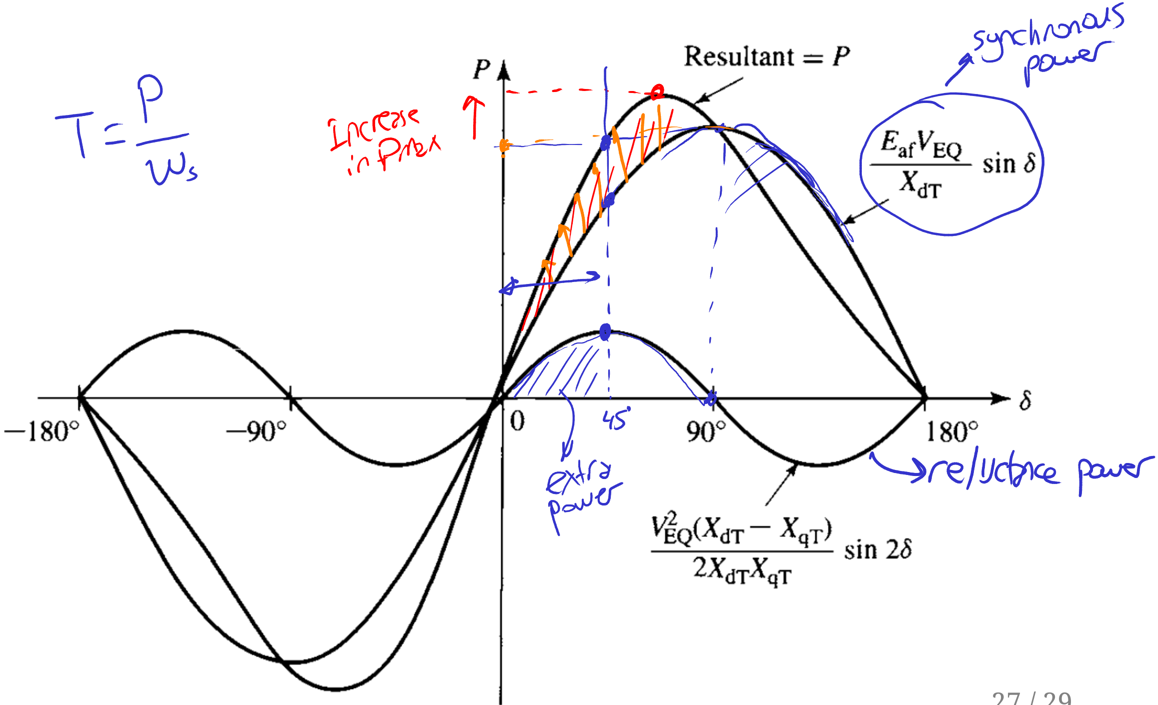
Total Power:

$$P = 3\left[\frac{V_t E_f}{X_d} sin(\delta) + \frac{V_t^2 (X_d - X_q)}{2X_d X_q} sin(2\delta)\right]$$

- First Term: Same with Cylindrical Machines
- Second Term: Reluctance Power (Independent of E_f, even exists if $I_f = 0$)

Power in Salient Pole Machines

$T = \frac{P}{\omega_s}$



Example:

A 3-phase star connected salient pole generator has a direct-axis impedance of 10Ω, and quadrature axis impedance of 6.5Ω.

Example:

A 3-phase star connected salient pole generator has a direct-axis impedance of 10Ω, and quadrature axis impedance of 6.5Ω.

If the generator is supplying 10 A, with a phase angle of 20 degrees lagging. Calculate:

Example:

A 3-phase star connected salient pole generator has a direct-axis impedance of 10Ω, and quadrature axis impedance of 6.5Ω.

If the generator is supplying 10 A, with a phase angle of 20 degrees lagging. Calculate:

a) Load Angle

Example:

A 3-phase star connected salient pole generator has a direct-axis impedance of 10Ω, and quadrature axis impedance of 6.5Ω.

If the generator is supplying 10 A, with a phase angle of 20 degrees lagging. Calculate:

a) Load Angle

b) D-Q components of the armature current

Example:

A 3-phase star connected salient pole generator has a direct-axis impedance of 10Ω, and quadrature axis impedance of 6.5Ω.

If the generator is supplying 10 A, with a phase angle of 20 degrees lagging. Calculate:

a) Load Angle

b) D-Q components of the armature current

c) Magnitude of Ef

You can download this presentation from:
keysan.me/ee362