


37-Power Angle

ECEGR 450
Electromechanical Energy Conversion



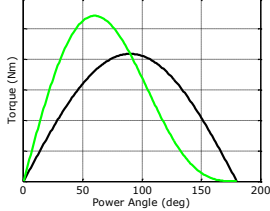
Torque vs Power Angle

Round Generator ($R_a = 0$)

$$T_d = \frac{3 |V_a| |E_a| \sin \delta}{X_s}$$


Salient-Pole Generator ($R_a = 0$)

$$T_d = \frac{3 |V_a| |E_a| \sin \delta}{X_d \omega_b} + \frac{3(X_d - X_q)}{2X_d X_q \omega_b} |V_a|^2 \sin(2\delta)$$



(generator, ignoring R_a)


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Power Angle (Round Rotor)

- Maximum torque (power) occurs at $\delta = 90^\circ$
- $0^\circ < \delta < 90^\circ$ for stability reasons

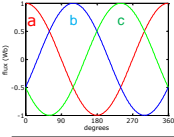
$$T_d = \frac{3 |V_a| |E_a| \sin \delta}{X_s}$$



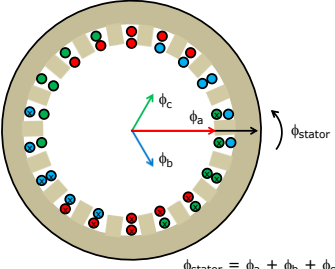
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Rotating Field




Notes:
Two-pole generator
A, B, C phase rotation
Stator flux rotates CCW
Stator current polarity at $t=0$ shown

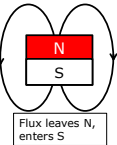


$\phi_{\text{stator}} = \phi_a + \phi_b + \phi_c$

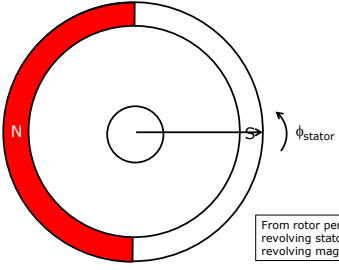
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Rotating Field




Flux leaves N, enters S

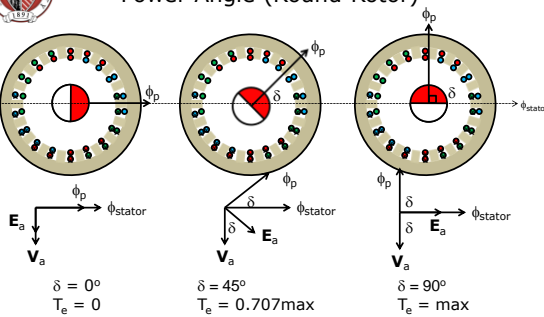


From rotor perspective:
revolving stator flux like
revolving magnet

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Power Angle (Round Rotor)



$\delta = 0^\circ$
 $T_e = 0$

$\delta = 45^\circ$
 $T_e = 0.707 \text{max}$

$\delta = 90^\circ$
 $T_e = \text{max}$

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Power Angle: Round Rotor Generator

Steady state operation:
 $T_e + T_m = 0$
 $T_{m,r} \omega$ in same direction: generator

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Power Angle: Round Rotor Motor

Steady state operation:
 $T_e + T_m = 0$
 $T_{e,r} \omega$ in same direction: motor

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Salient Pole Machines

- Decompose torque into rotor pole and salient pole torque

$$T_d = \underbrace{\frac{3}{2} \frac{V_a |E_a| \sin \delta}{X_d \omega_s}}_{\text{torque developed by rotor pole}} + \underbrace{\frac{3(X_d - X_q)}{2X_q X_q \omega_s} |V_a|^2 \sin(2\delta)}_{\text{Torque developed due to saliency}}$$

- Maximum occurs between 45 and 90 degrees (dependent on $|V_a|$, $|E_a|$, X_d and X_q)

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Effect of Saliency

Black: $X_d = X_q = X_s$ (round rotor)
 Red: $X_d = 1.2X_q = X_s$
 Blue: $X_d = 1.5X_q = X_s$
 Green: $X_d = 2X_q = X_s$

Note: maximum torque occurs at different power angles

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Power Angle (Unexcited Salient Pole)

Consider a salient-pole motor with no excitation

$$T_d = -3 |V_a|^2 \sin(2\delta) \left[\frac{X_d - X_q}{2X_q X_q \omega_m} \right]$$

No torque Torque CW No net torque Torque CCW

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Power Angle (Unexcited Salient Pole)

Mech. angle = 0°
 $T_e = 0$

Mech. angle = 45°
 $T_e = \text{max}$

Mech. angle = 90°
 $T_e = 0$

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