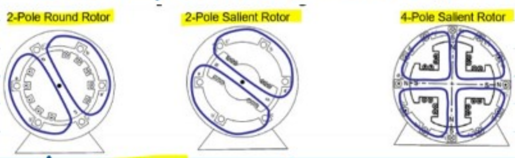
6. Synchronous Machines

Monday, November 30, 2020 5:16 AM

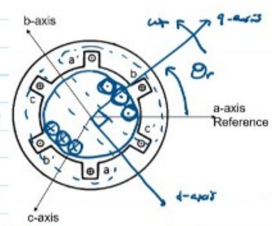
Synchronous Machines
- Cylindrical/Round pole Rotors → High speed Machines, ↓ # poles
- Salient pole Rotors → Low speed machines, ↑ # poles



- $f_e = 60Hz$ → const

$\omega_e = 2\pi f_e$ $n_{syn} = \frac{120}{P} f_e$ → rotor speed & freq of induced voltage

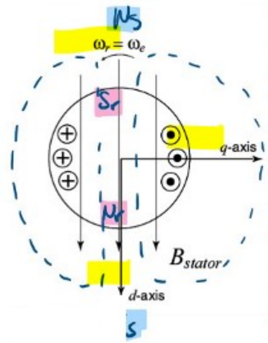
Direct & Quadrature Axis



- Convert P-pole → 2-pole w/ P/2 factor
  - Eg. 2-pole motor speed: $\omega_r = \frac{P}{2}\omega_{rm}$ → actual mech speed (smaller)
- @ steady state: $\omega_r = \omega_e$
  - ↳ $\theta_r = \frac{P}{2}\theta_{rm}$
- $\omega_r = \frac{2}{P}\omega_e$

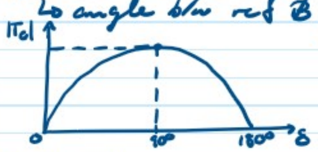
Principle of operation

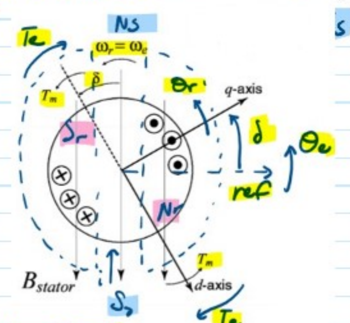
Idle Mode



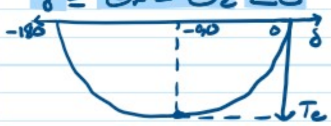
- Assume no external Torque: $T_m = 0$
- Rotor poles synchronized w/ stator field
- Rotor poles aligned w/ stator poles
- No torque produced $T_e = 0$

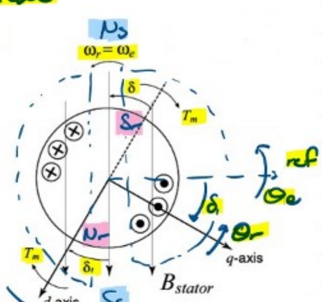
Generating
- Apply external torque $T_m > 0$
  - ↳ in d.r. of rotation
- Rotor poles synchronized w/ stator field
- Rotor poles lead stator poles
- Torque produced T_e
  - $\delta = \theta_r - \theta_e > 0$
  - ↳ angle b/w ref & q-axis



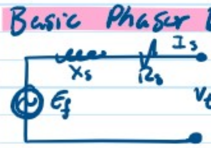


Motoring
- Apply external Torque $T_m < 0$
  - ↳ in opp dir. of rotation
- Rotor poles synchronized w/ stator field
- Rotor poles lag stator poles
- Torque produced T_e
  - $\delta = \theta_r - \theta_e < 0$





Basic Phasor Diagrams



- φ → PF angle b/w V_t & I_s
- δ → Angle b/w V_t & E_f
  - → Motoring: ← I_s
  - → Generating: I_s →

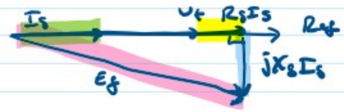
Motor
$V_t = (R_s + jX_s)I_s + E_f$

- Lagging PF:

@ PF = 1: (unity)

↳ Consuming Reactive Power $(Q \rightarrow +)$
↳ I_s lagging V_t

@ PF = 1: (unity)



– **leading PF:**

↳ Producing Reactive power $(Q \rightarrow -)$
↳ I_s leading V_t

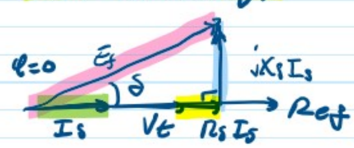
Generator

$V_t = E_f - (R_s + jX_s)I_s$

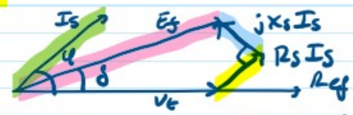
– **lagging PF:**

↳ Consuming Reactive Power $(Q \rightarrow +)$
↳ I_s lagging V_t

@ PF = 1: (unity)

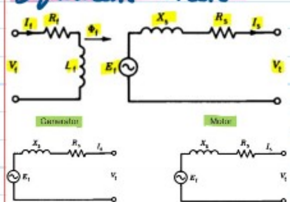


– **leading PF:**



↳ Producing Reactive ower $(Q \rightarrow -)$
↳ I_s leading V_t

Equivalent Circuit



Synchronous Reactance: $X_s = \omega_e L_s = X_{ms} + X_{ls}$ → $R_s << X_s$
Synchronous Impedance: $Z_s = R_s + jX_s$

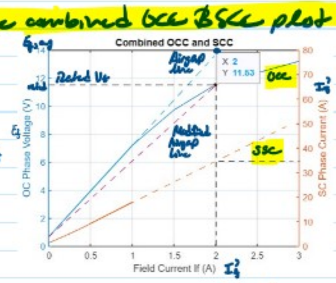
– V_f → Field (excitation) winding
– V_t → Stator (Armature) winding

$V_t = \pm(R_s + jX_s)I_s + E_f$

Determination of Parameters

1. Measure DC: $R_s = \frac{V_{dc}}{2I_{dc}}$, $R_f = \frac{V_{f,dc}}{I_{f,dc}}$
2. Open-Circuit Test (E_f)
3. Short Circuit Test (Z_s, X_s)

Use combined OCC & SCC plot



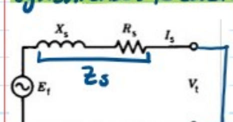
Open Circuit Test

– Measure Phase Voltage ($V_t = E_{f,rated}$)
– Measure Field current I_f'
– Use OCC characteristics to find I_f then I_s

Short Circuit Test

– Measure Phase Current $I_{s,rated}$
– Measure Field Current I_f''

Synchronous Reactance



$E_f = (R_s + jX_s)I_s = Z_sI_s \approx X_sI_s$ → $I_s = \frac{S_{rated}}{\sqrt{3}V_{line}}$

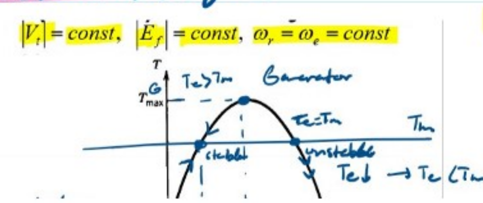
$Z_{s,unsat} = \frac{E_{f,ag}}{I_s'}$ $\quad Z_{s,sat} = \frac{E_{f,rated}}{I_s'}$

$X_{s,unsat} = \sqrt{Z_{s,unsat}^2 - R_s^2}$ $\quad X_{s,sat} = \sqrt{Z_{s,sat}^2 - R_s^2}$

– **Short Circuit Ratio (SCR):** $SCR = \frac{I_s'}{I_{s,rated}} = \frac{I_f'}{I_f''} = \frac{E_{f,rated}}{I_{s,rated}Z_{s,rated}} = \frac{1}{Z_{s,sat}^{pu}} \approx \frac{1}{X_{s,sat}^{pu}}$
↳ Ratio of steady state SC current / nominal (rated) current

Real Power & Torque

$|V_t| = const,\ |\dot{E}_f| = const,\ \omega_r = \omega_e = const$



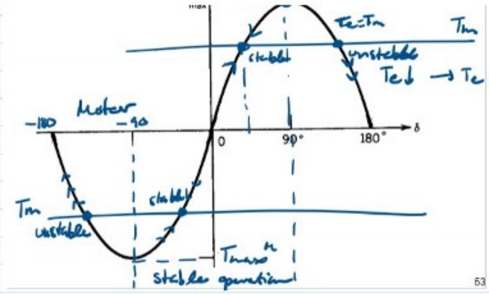
Real Power: $P = VI\cos\varphi$ → $E_f\sin(\delta) = X_sI_s\cos(\varphi)$

$P_{3\varphi} = 3\frac{V_tE_f}{X_s}\sin(\delta) = \omega_{syn}T_e$

Torque: $T_e = \frac{3}{\omega_{syn}}\frac{V_tE_f}{X_s}\sin(\delta)$

$P_{max} = 3\frac{V_tE_f}{X_s}$

Torque: $T_e = \frac{3}{\omega_{syn}} \frac{V_t E_f}{X_s} \sin(\delta)$



$P_{max} = 3\frac{V_t E_f}{X_s}$

$T_{max} = \frac{P_{max}}{\omega_{syn}}$

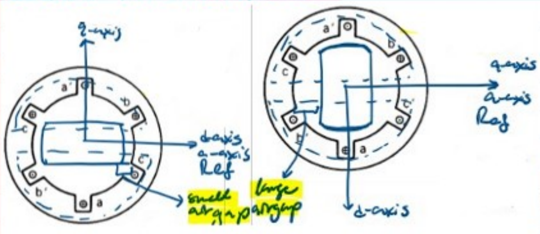
Reactive Power: $Q = VI\sin\varphi$ → $E_f\cos(\delta) = V_t + X_s I_s \sin(\varphi)$

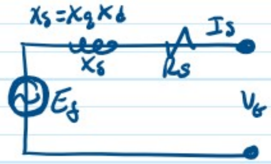
$Q_{3\varphi} = 3\,\frac{V_t E_f \cos(\delta) - V_t^2}{X_s}$ → $V_t E_f$ = reactive power control (I_f)

↳ $Q > 0$ → Capacitive, leading PF

$Q < 0$ → Inductive, lagging PF

Salient Pole Machines





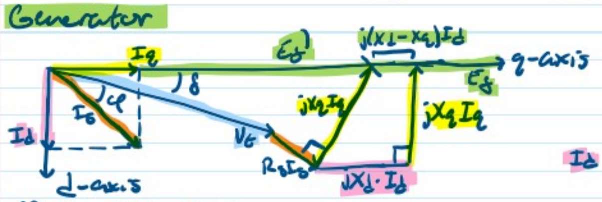
$\underbrace{L_q}_{small} = \frac{N^2}{\underbrace{R_q}_{large}}$ $\quad \underbrace{L_d}_{large} = \frac{N^2}{\underbrace{R_d}_{small}}$

$X_q = X_{mq} + X_{ls}$

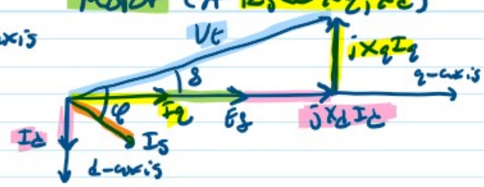
$X_d = X_{md} + X_{ls}$

- Stator Current: $I_s = I_q + I_d$
- Voltage Eqn.: $E_f = \underbrace{V_t + R_s I_s + jX_q I_q}_{E_f'} + \underbrace{jX_d I_d}_{}$ $\quad$ $j(X_d - X_q)I_d$

Generator



Motor (If $R_s \ll X_q, X_d$)



If $R_s \ll X_q, X_d$: