ELEC 342
Electromechanical Energy Conversion and Transmission

2025-26 Winter Term 2

Lecture 20

March 24, 2026

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Course Logistics

- Lab 4 takes place this week
- Lab 5 Monday section moved to Wednesday (Apr. 8) at 10:30 AM
  - Only Monday section is modified, Friday sections are not impacted
- Quiz 4 takes place at the beginning of lecture on Apr. 2
- SEI survey: March 28 – April 13
- Final exam: Apr. 19 @ 12 PM in IRC 4

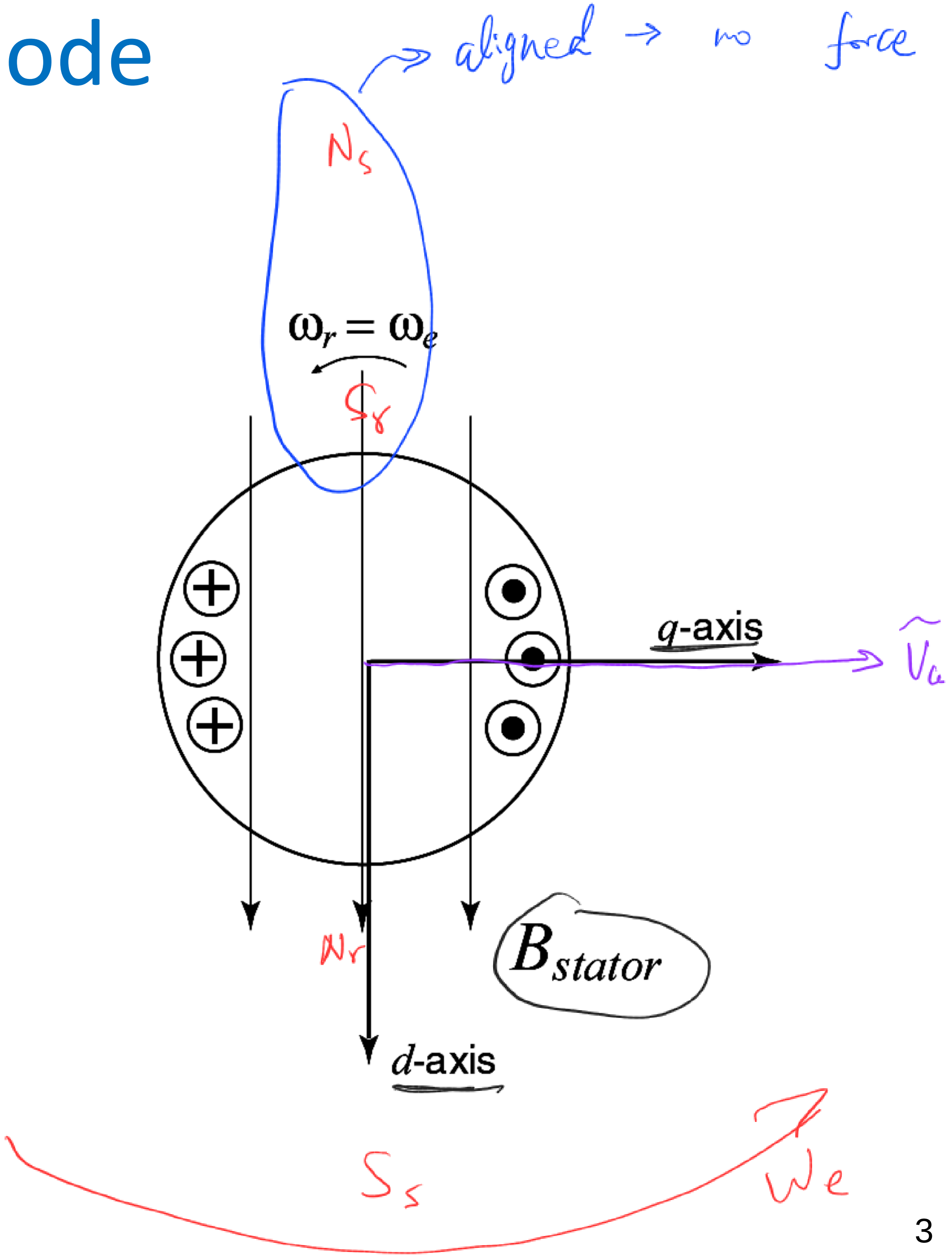
Principle of Operation – Idle Mode

a) Assume no external torque $T_m = 0$

- Rotor poles are synchronized with the stator field
- Rotor poles are aligned with stator poles
- No torque produced $T_e = 0$

Stator voltage phasor : $\tilde{V}_a$

↳ Inductive

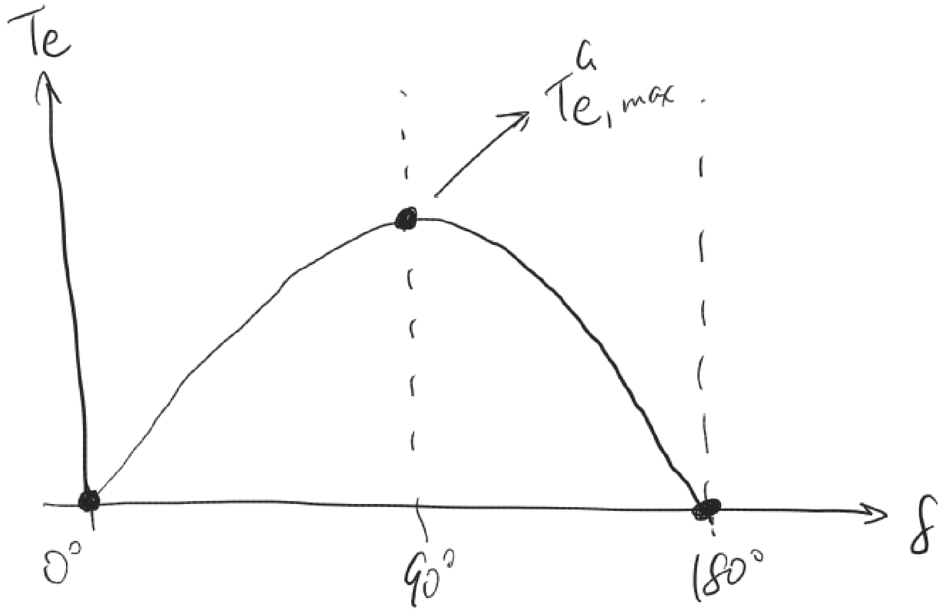


Principle of Operation - Generating

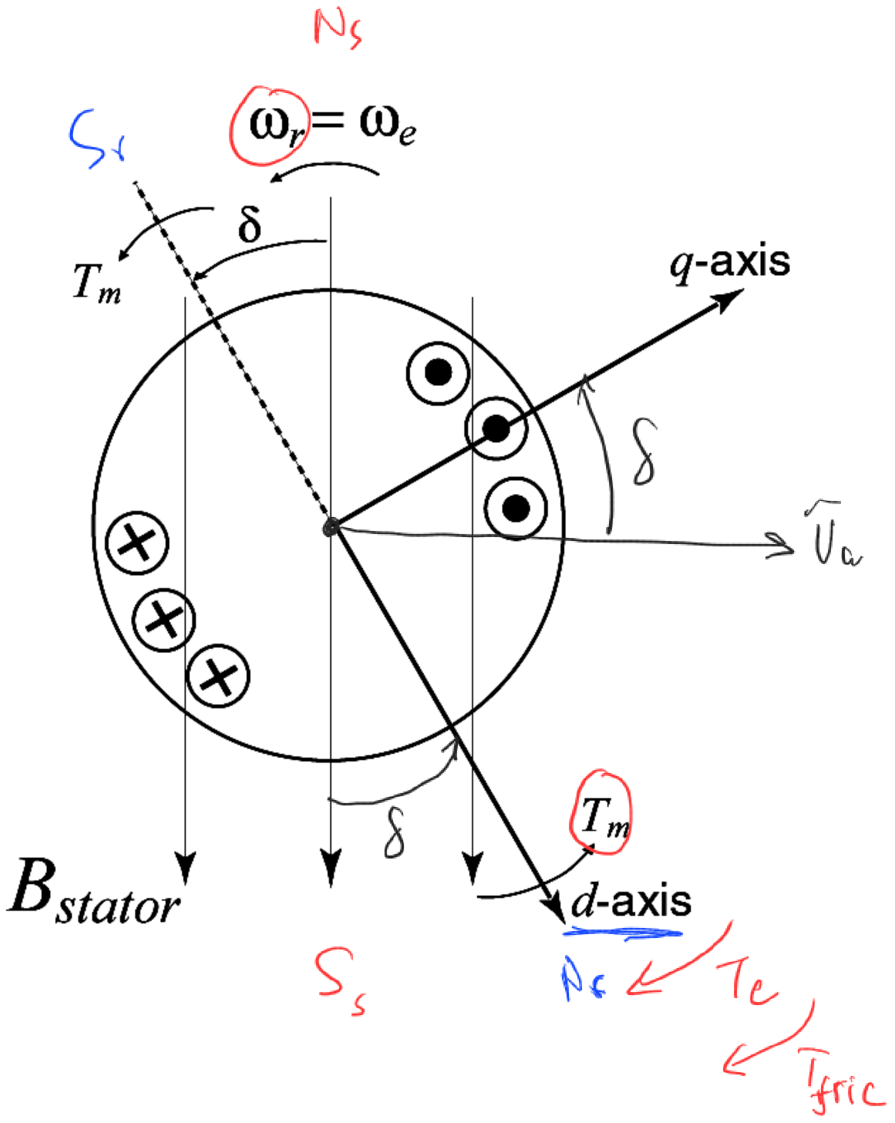
b) Apply external torque $T_m > 0$
in the direction of rotation

- Rotor poles are synchronized with the stator field
- Rotor poles **lead** stator poles
- Torque is produced T_e

$\delta = \theta_r - \theta_e > \phi$ (Generating)



loss of sync. (no opposing Te to Tm anymore)

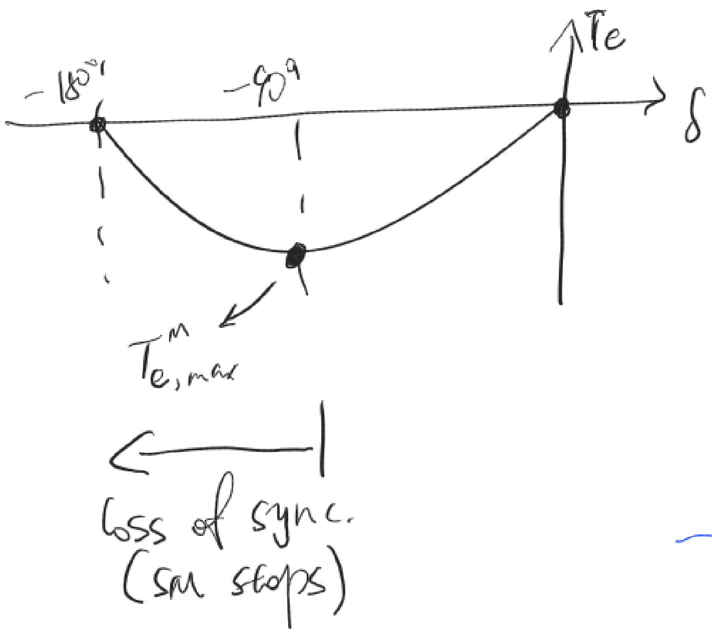


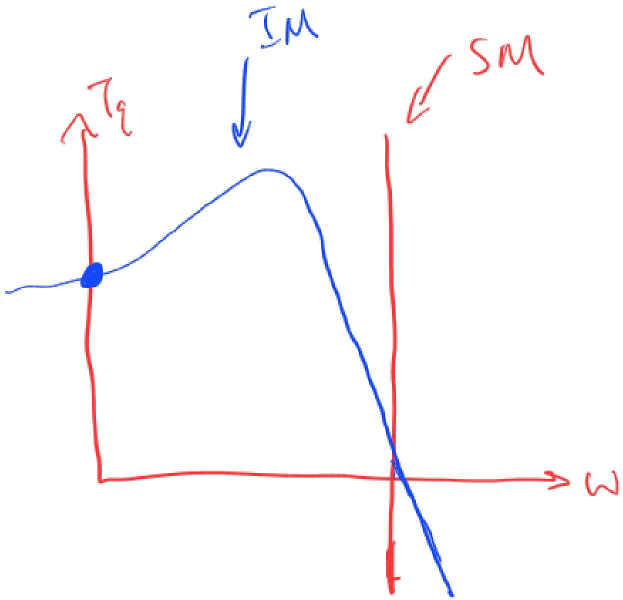
Principle of Operation - Motoring

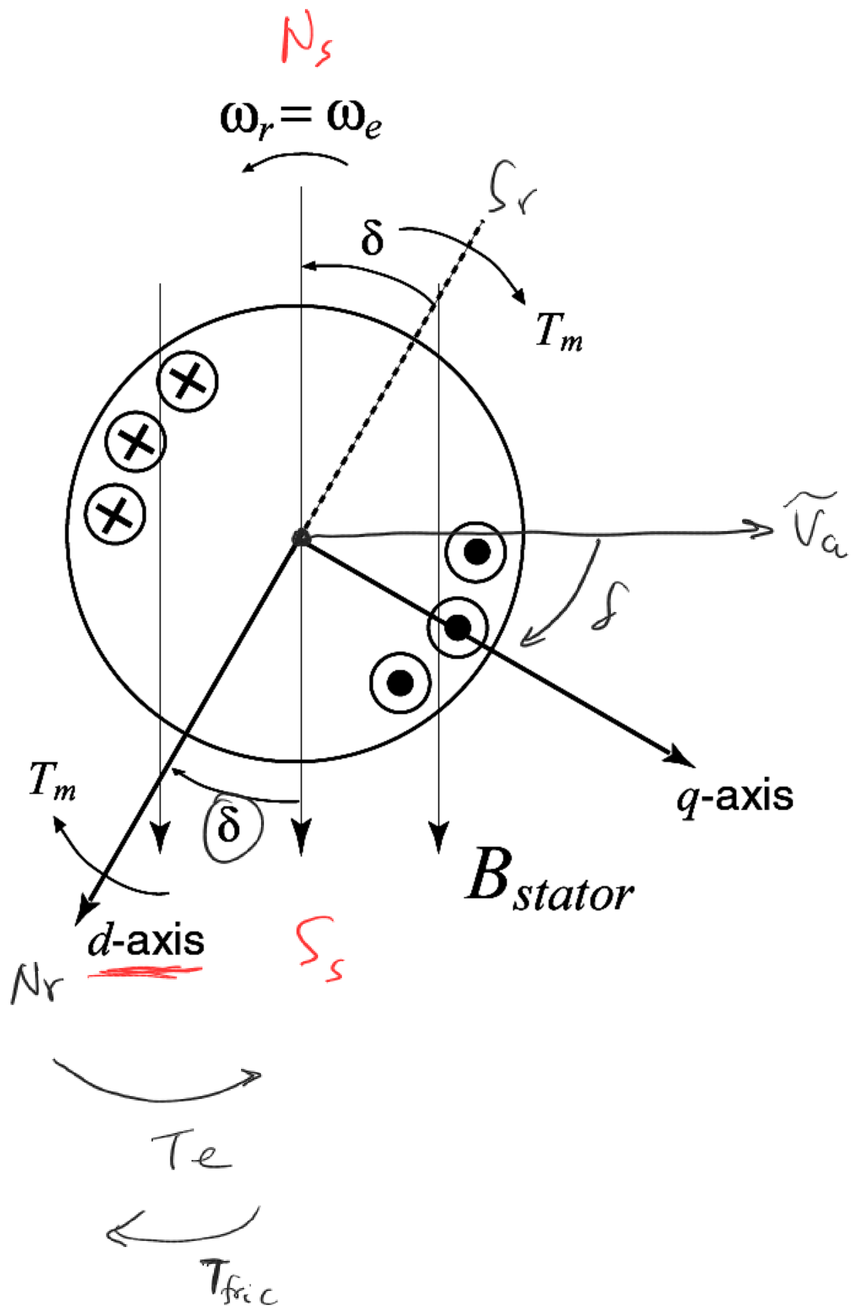
c) Apply external torque $T_m < 0$
in the direction opposite to rotation

- Rotor poles are synchronized with the stator field
- Rotor poles **lag** stator poles
- Torque is produced T_e

$\delta = \theta_r - \theta_e < \emptyset$ (motoring)

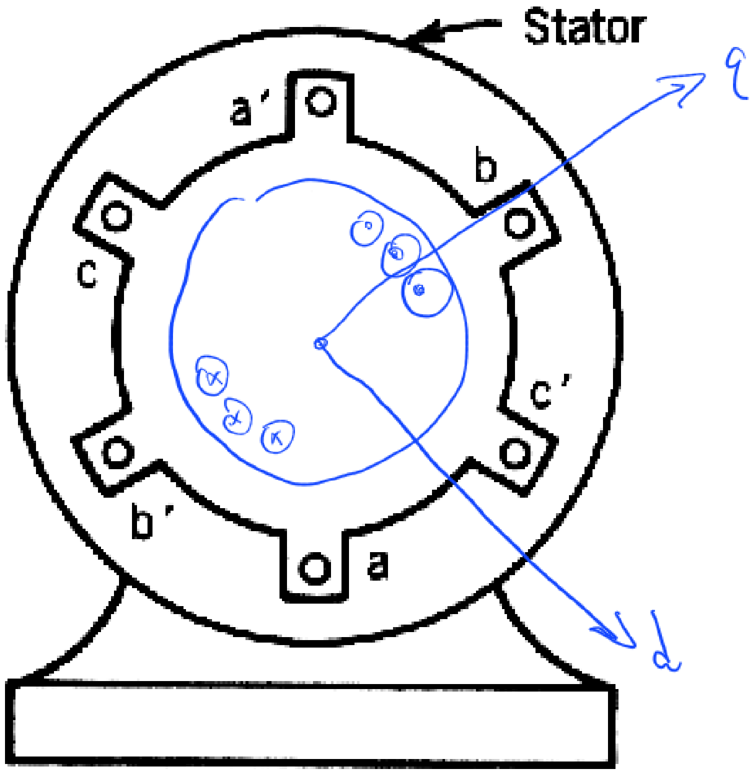




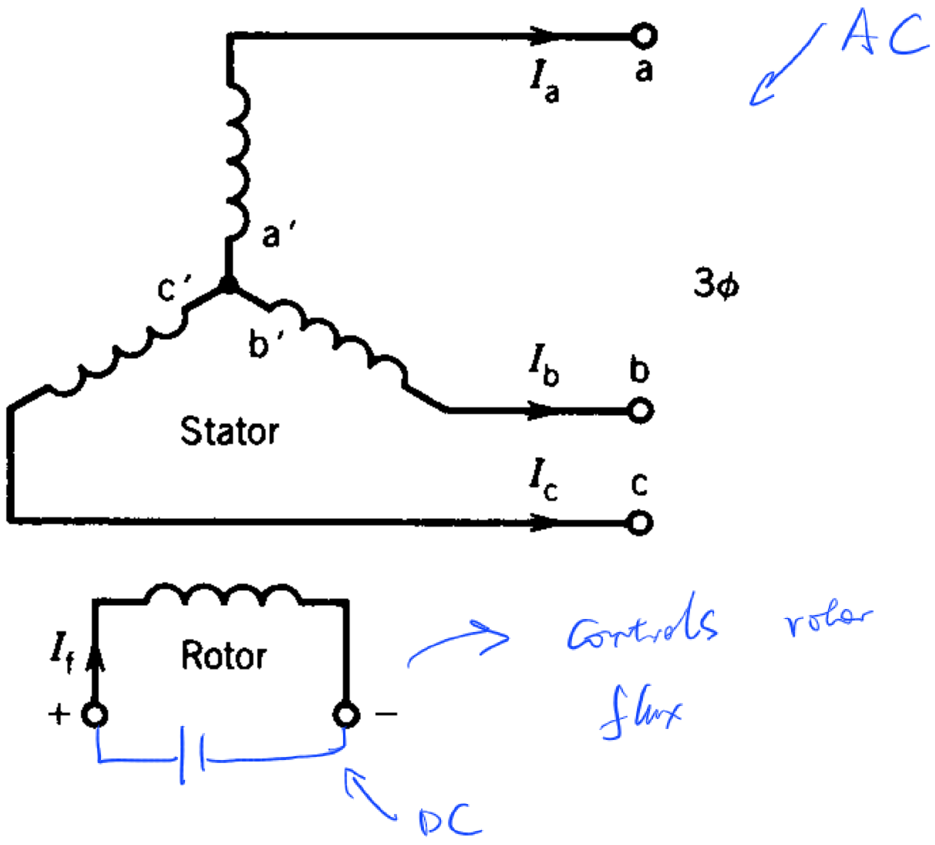


Induced Voltage on Stator Windings

Assume round rotor



Rotor flux is DC
↳ Rotor rotates in space
↳ induces voltage on stator windings

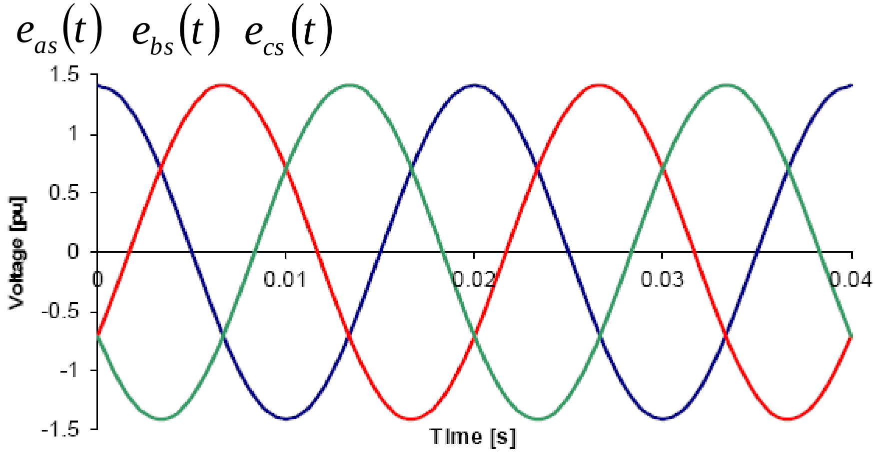


For machines with field winding

$$E_a \sim L_{sf} I_f \omega_r$$ $\propto f$

For PM machines

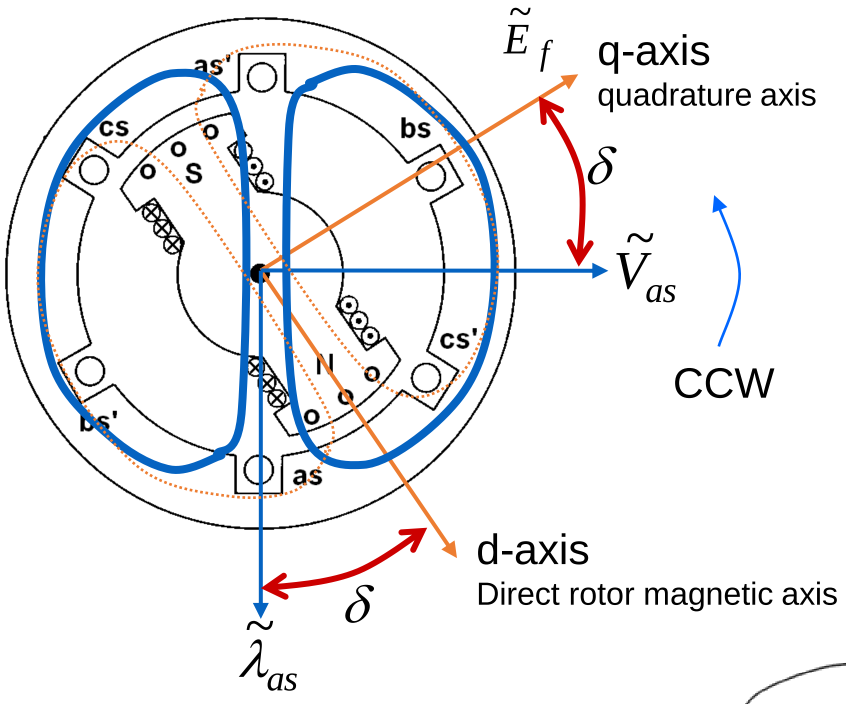
$$E_a \sim K_v \omega_r$$

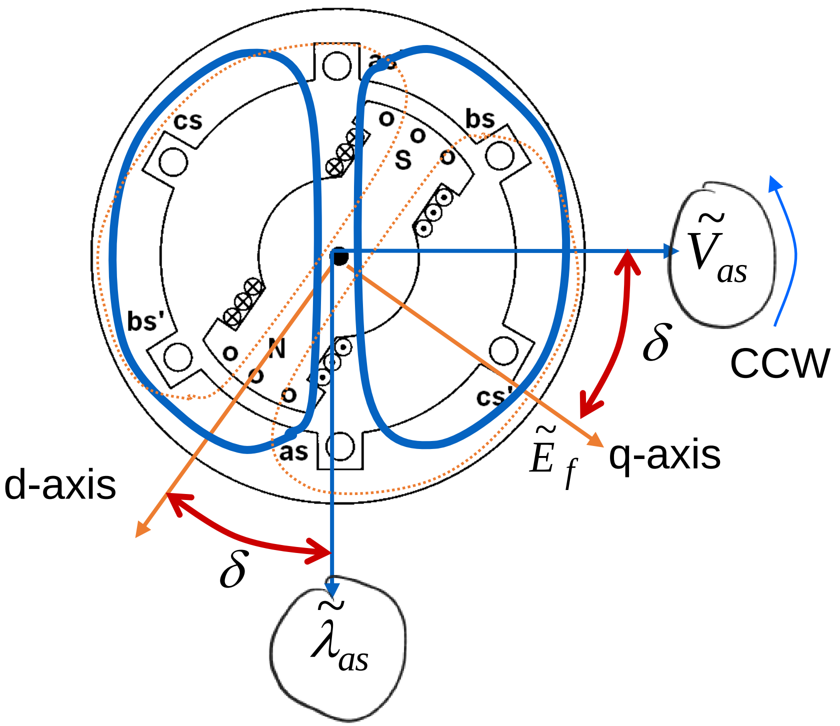


Generating & Motoring Modes

Rotor is leading stator rotating field
=> Generating Mode

Rotor is lagging stator rotating field
=> Motoring Mode





Rotor Angle $\delta = \theta_r - \theta_e$

misalignment

Electrical displacement angle and
Rotor position angle

$$\theta_e = \int \omega_e dt$$

$$\theta_r = \int \omega_r dt$$

Stator rotating magnetic field

$$v_{as} = \frac{d\lambda_{as}}{dt} \Rightarrow \lambda_{as} = \int v_{as} dt$$

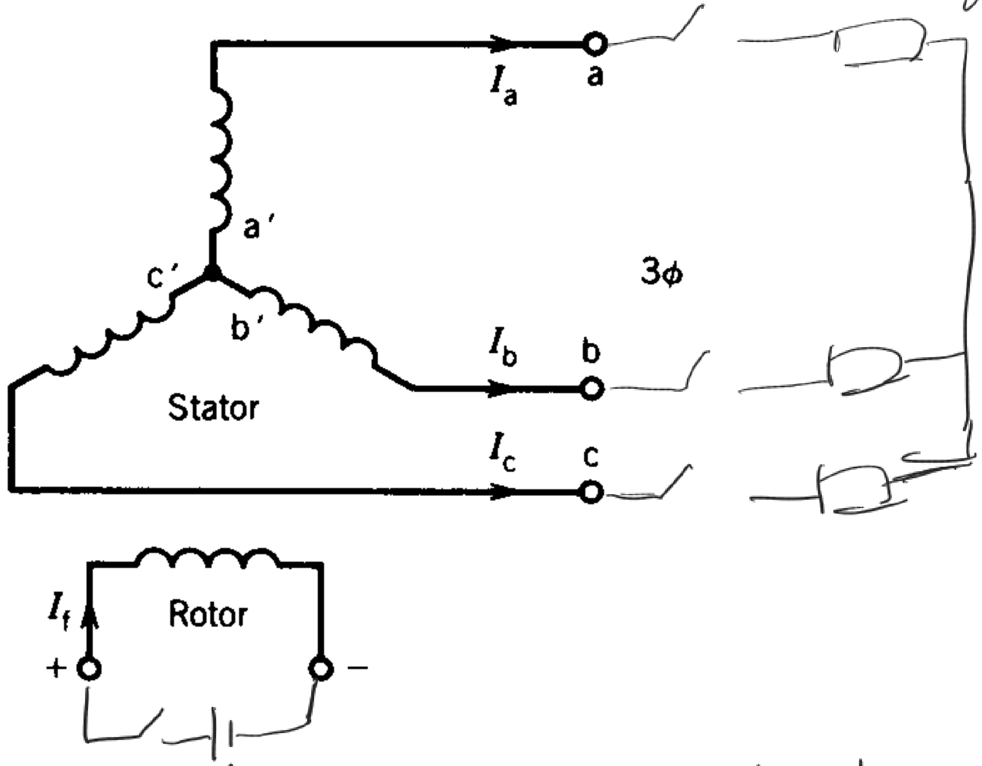
Starting Synchronous Generator

IM: torque comes from asynchronism → self-start
SM: torque comes from synchronism → need external device to start

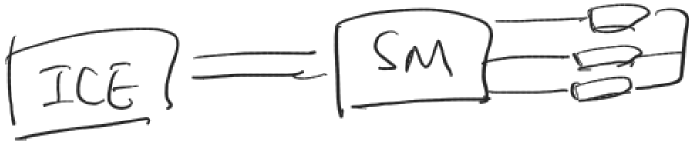
- Stand-alone generator

ICE

diesel generator



DC source like battery



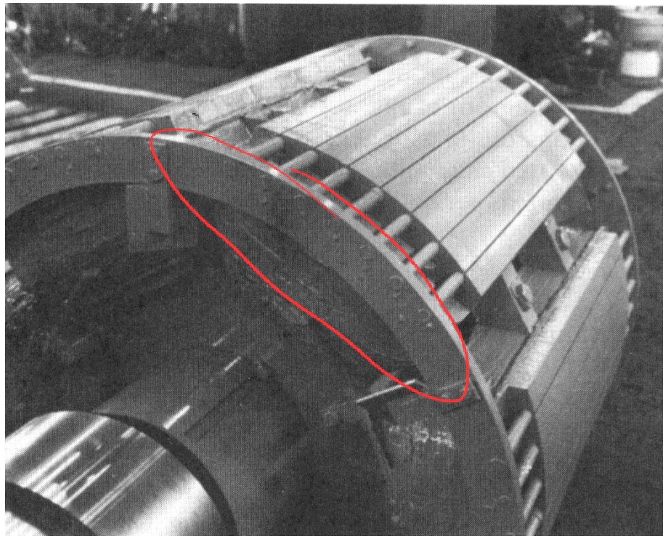
1. Bring the generator speed to the level that corresponds to the desired frequency (60Hz)
2. Apply the field voltage (field current) to produce the desired (rated) output voltage
3. Connect the load

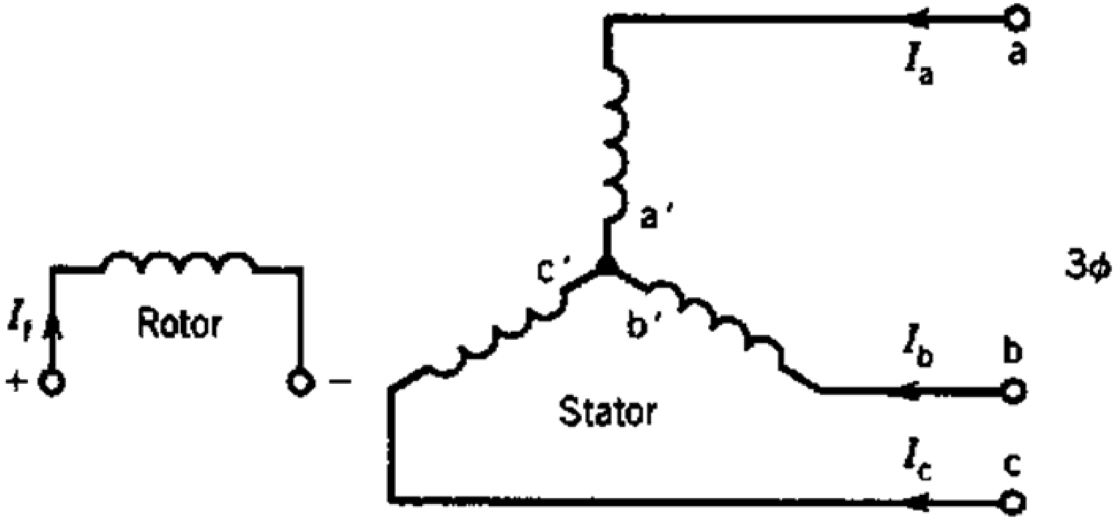
Starting Synchronous Motor

PD controller

Start as an Induction Motor (using damper windings)

- May be used with small to medium machines

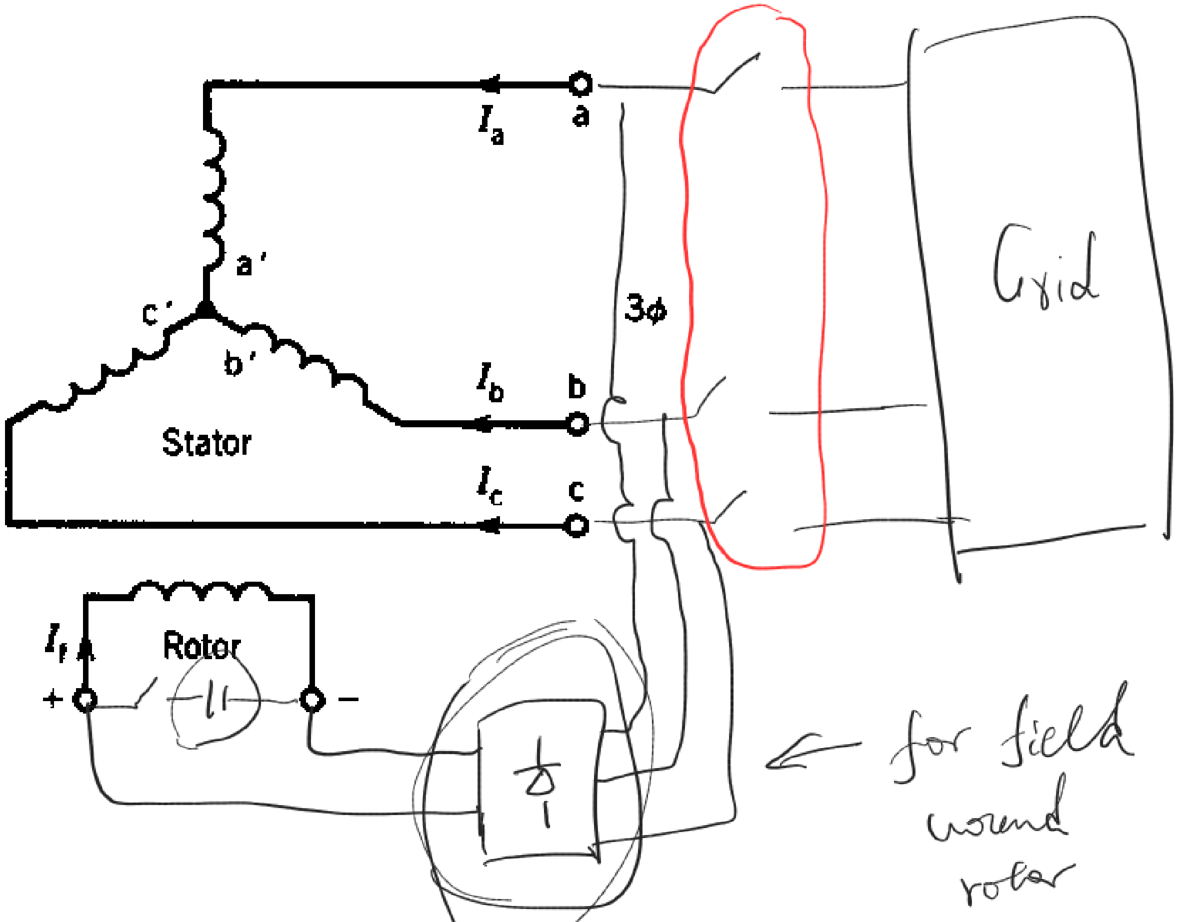




1. Apply voltages to the stator with no mechanical load on the shaft
2. Let the motor reach the steady-state speed close to synchronous speed
3. Apply the field voltage (field current) to produce the rotor field
   => The rotor poles should lock to the stator field (at synchronous speed)

Starting Synchronous Machine

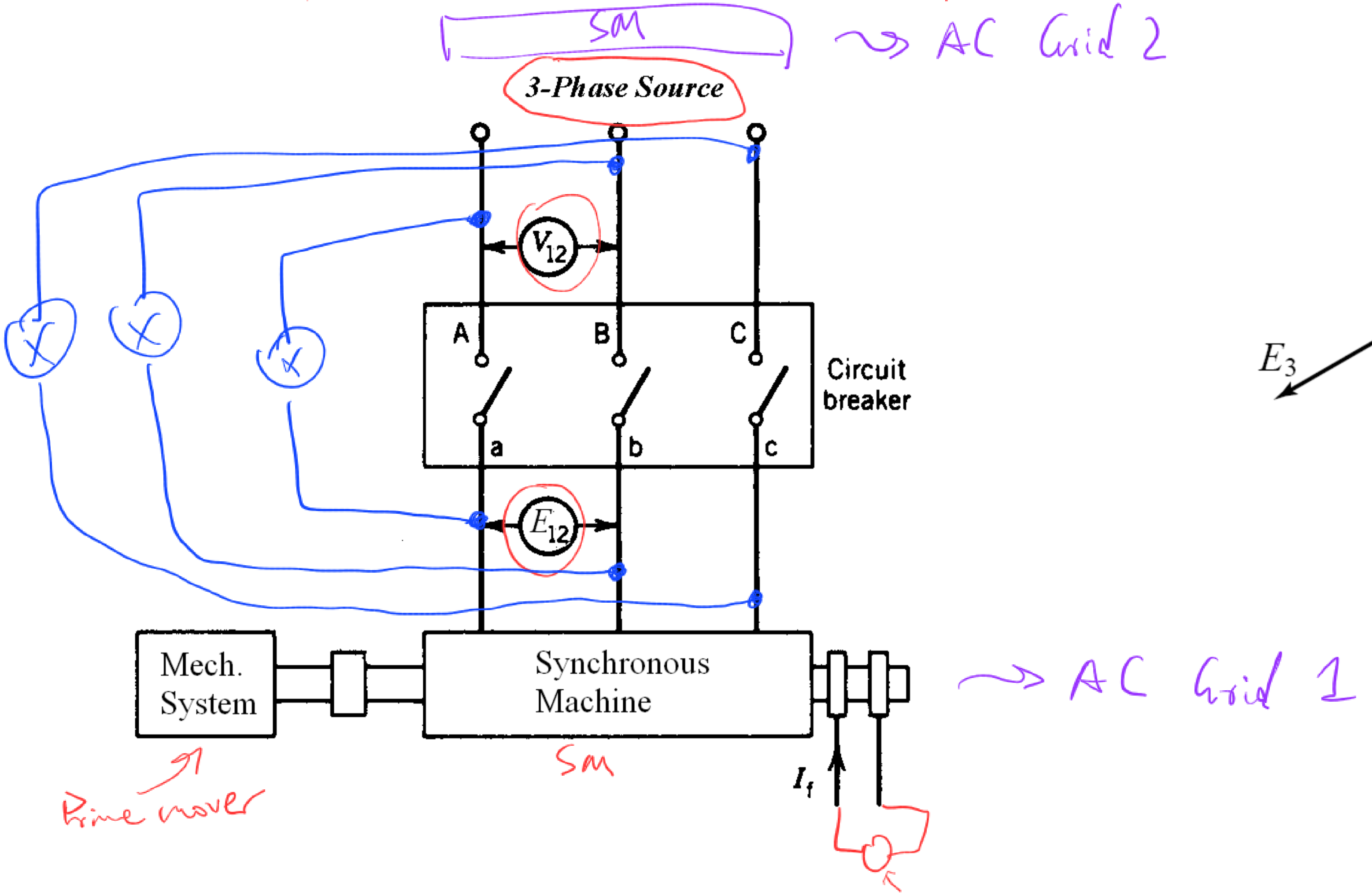
Start using auxiliary (prime mover) motor (using a smaller motor)

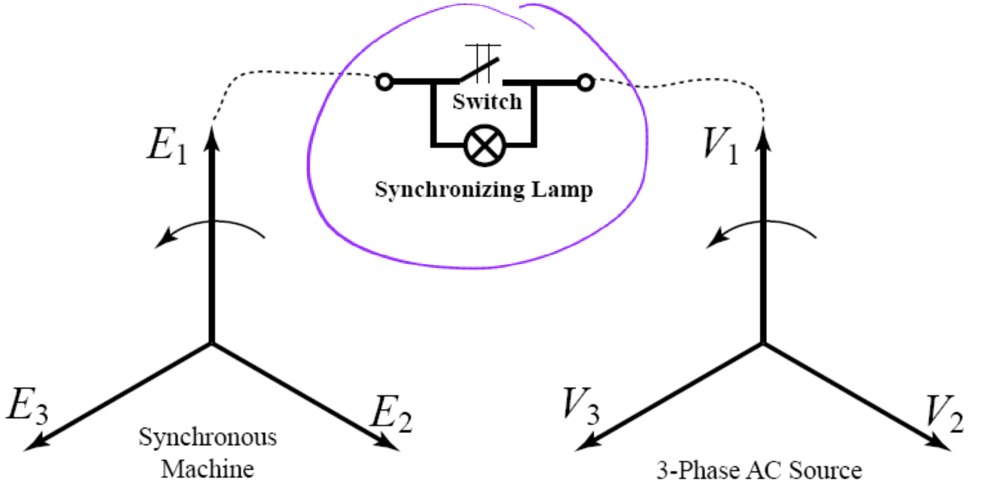


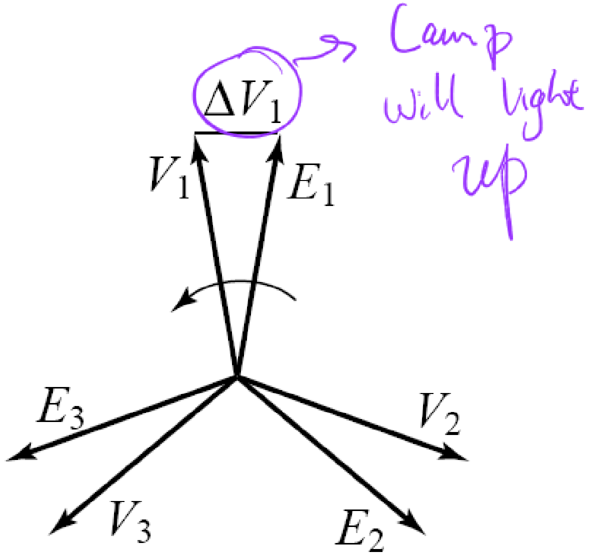
1. Start the prime mover motor, and slowly bring the speed on large SM close to synchronous
2. Apply the field voltage (field current) to the main SM to generate voltages in the stator winding
3. When the induced (generated) voltages are the same as the grid voltages, connect the SM to the grid
4. The rotor poles should lock with the stator field (at synchronous speed)

Connecting Synchronous Machine to Grid → Lab 5

$$E_a \sim L_{sf} I_f \omega_r \sim K_v \omega_r$$

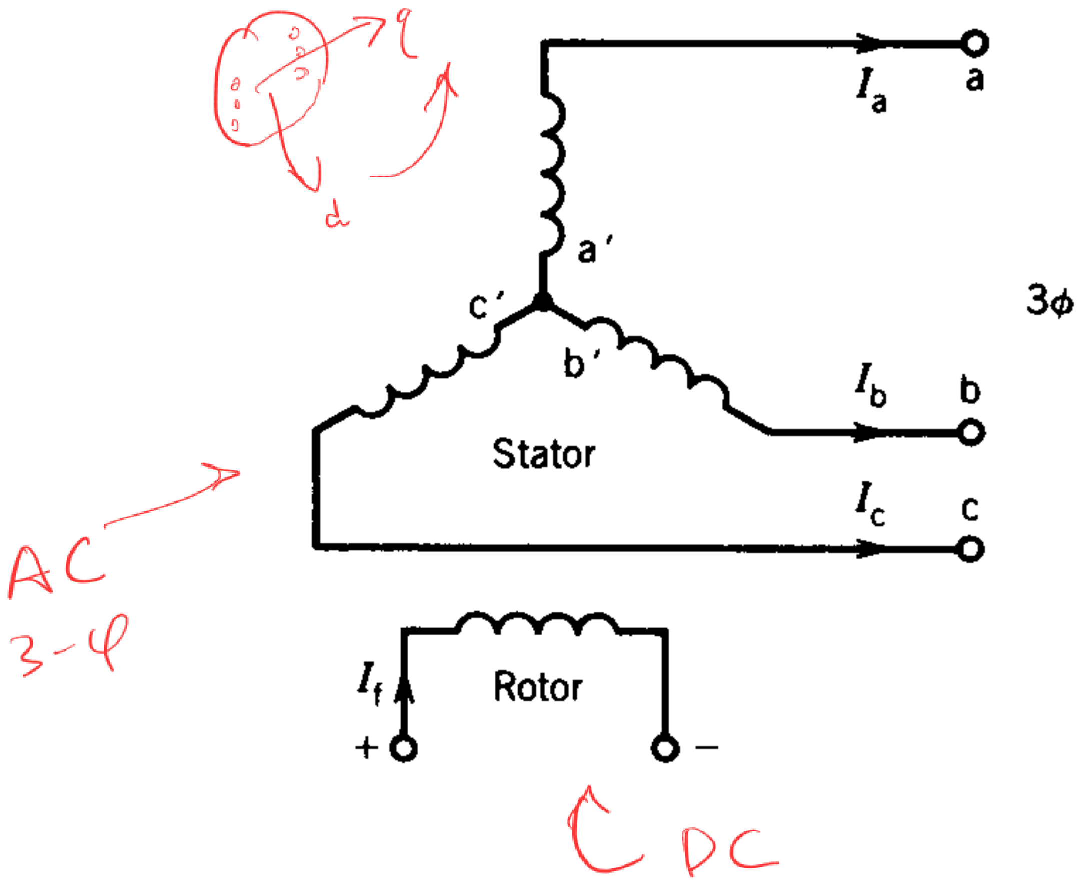


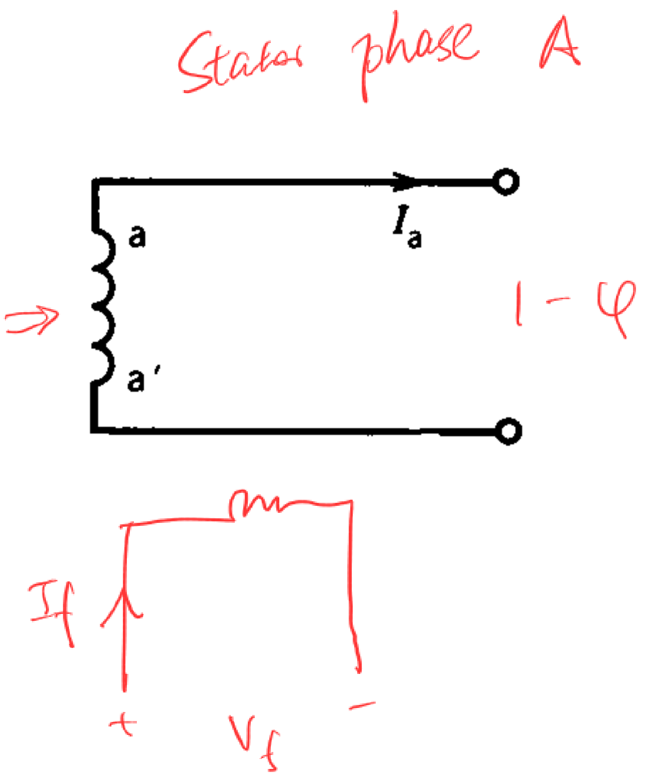




1. Make sure that Syn. machine and grid voltages have same sequence (*ABC* & *abc*)
2. Bring the Syn. machine speed corresponding to the same frequency of grid (60Hz)
3. Adjust the Syn. machine (e.g., by field current) and/or grid voltages to have same amplitude
4. Adjust/make sure the Syn. machine and grid voltages have same phase
5. Close the connecting switch

Per-phase Equivalent Circuit





- Assume balanced and symmetrical 3-phase Generator & Load
- Develop Equivalent Circuit for one phase
- Extend the results to 3-phase case

Per-phase Equivalent Circuit

field loss → $I_f^2 R_f$

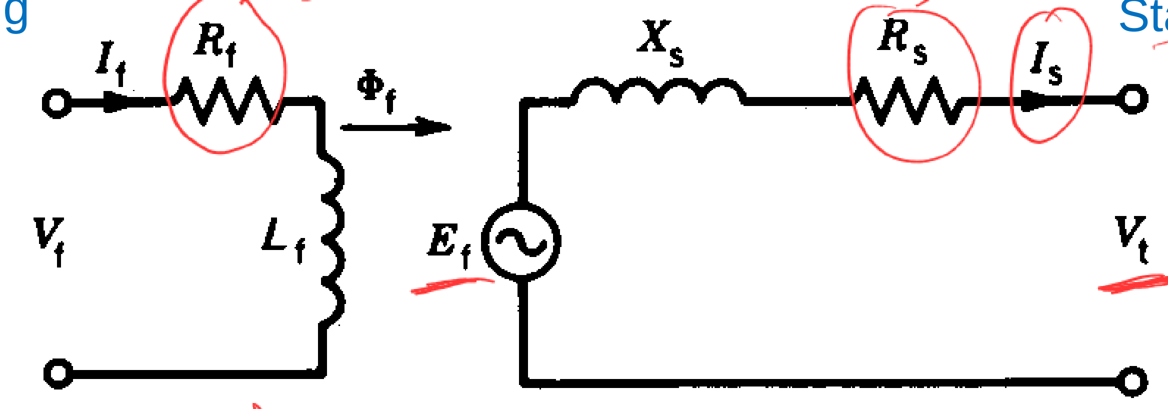
stator loss → $3 I_s^2 R_s$

Field (Excitation) winding

separately excited

Stator (Armature) winding

rotating field



stator

rotor

DC

V_f - Field winding voltage

I_f - Field current

R_f - Field winding resistance

L_f - Field winding inductance

Φ_f - Flux due to the rotor field

$$\lambda_f = N_f \Phi_f = L_f I_f$$

AC

V_t - Terminal voltage

I_s - Stator (armature) current

R_s - Stator (armature) winding resistance

$X_s = \omega L_s$ - Synchronous reactance

$Z_s = R_s + jX_s$ - Synchronous impedance

E_f - Induced back emf (open-circuit voltage), Excitation Voltage (in the book)

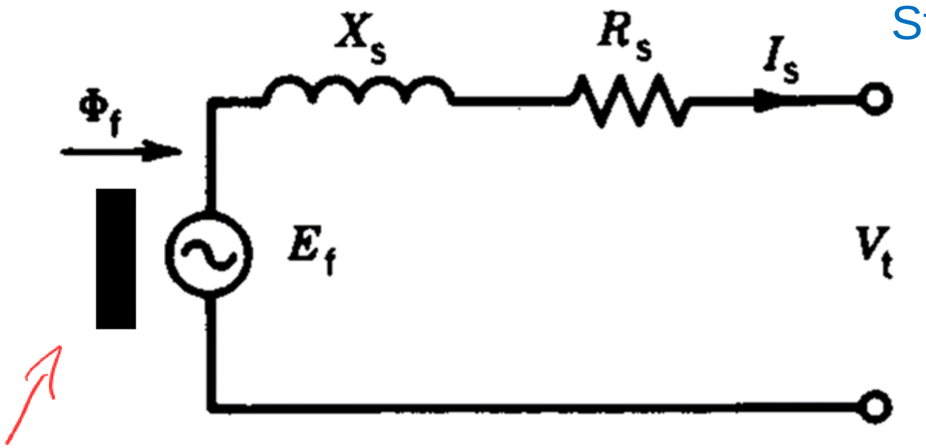
Typically, for large machines $R_s << X_s$

Per-phase Equivalent Circuit

For PM Machines

$$\lambda_f = K_v$$

$$E_f = K_v \omega_r$$



AC

V_t - Terminal voltage

I_s - Stator (armature) current

R_s - Stator (armature) winding resistance

$X_s = \omega L_s$ - Synchronous reactance

$X_s >> R_s$

$Z_s = R_s + jX_s$ - Synchronous impedance

E_f - Induced back emf (open-circuit voltage), Excitation Voltage (in the book)

Determination of Parameters

For PM Machines

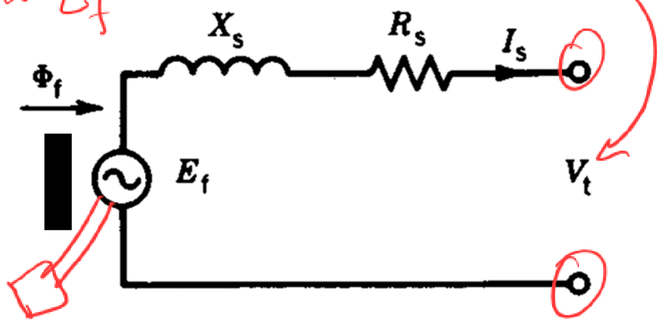
1) Open-circuit test

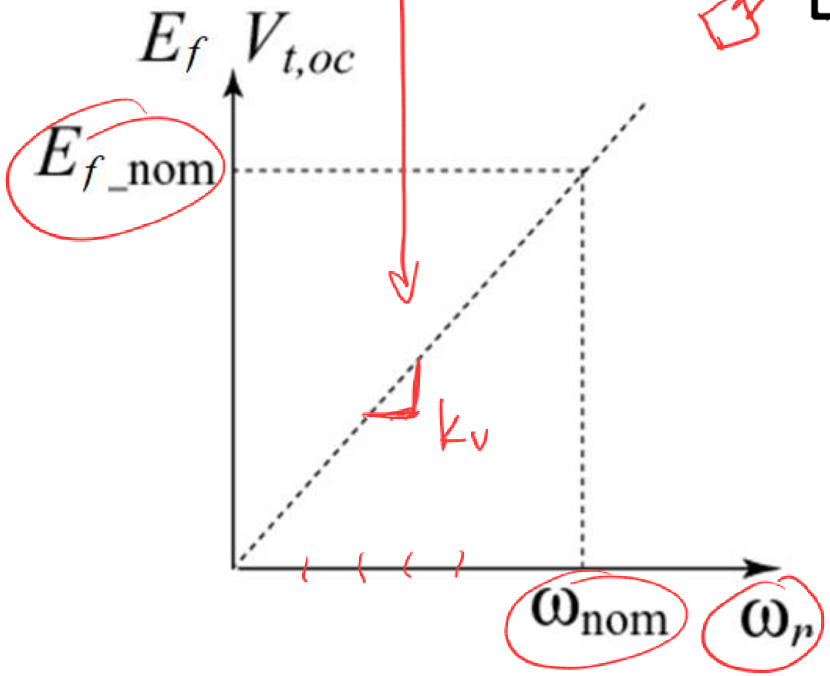
- Spin the machine by external prime mover
- Record the output terminal voltage

at different ω_r

↳ equal to E_f

$$E_f = K_v \omega_r$$





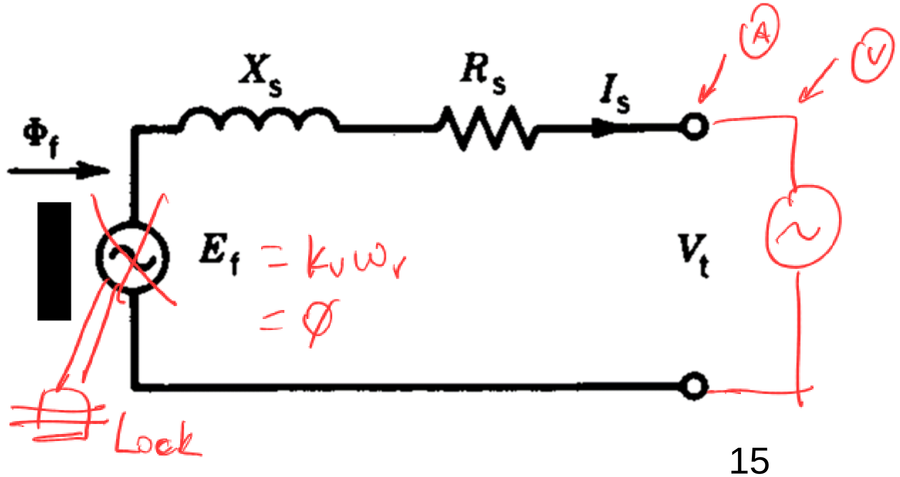
2) Stall-rotor test

- Lock rotor, and slowly apply AC voltage to stator terminals
- Record the output terminal voltage and current
- Calculate the stator impedance

$$Z_s = \frac{V_s}{I_s} = R + jX$$

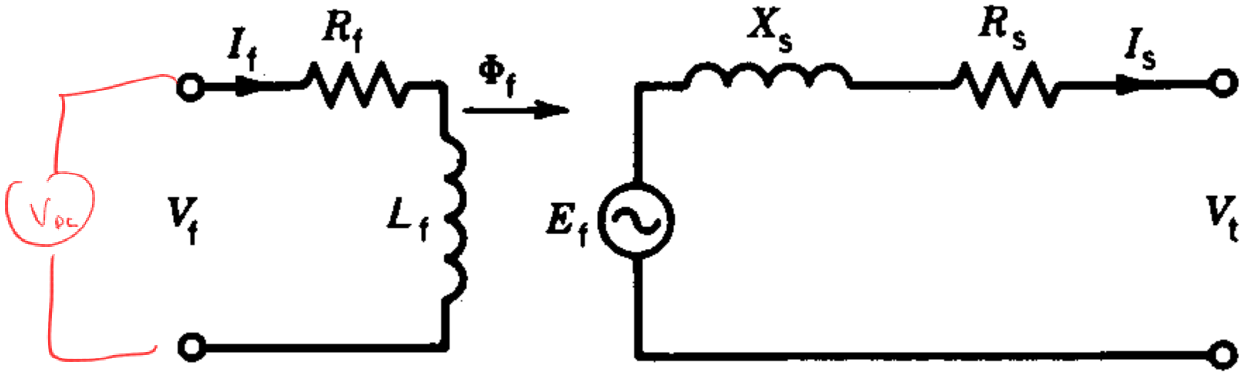
phasors

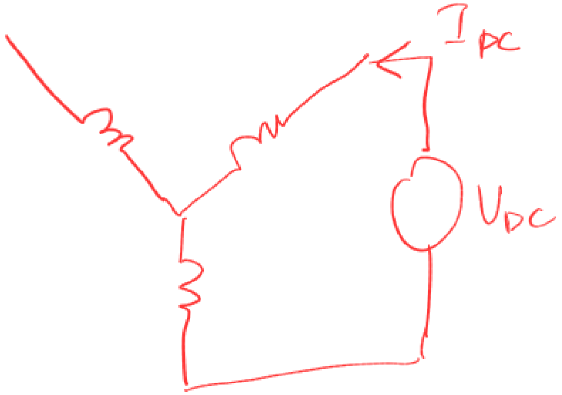
split



Determination of Parameters

For Field-wound Synchronous Machines

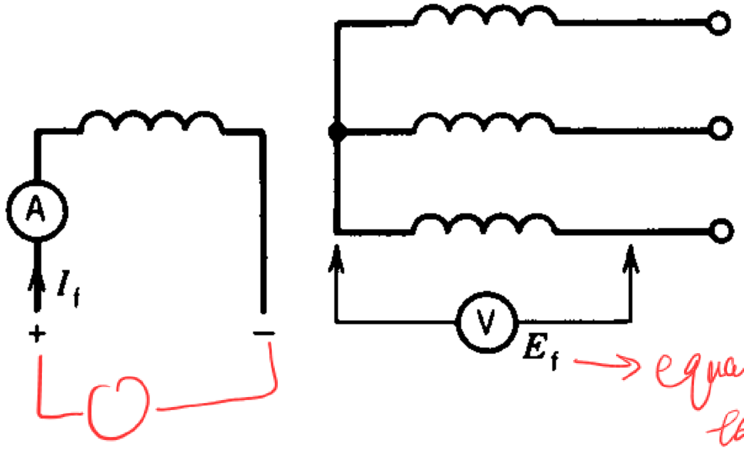




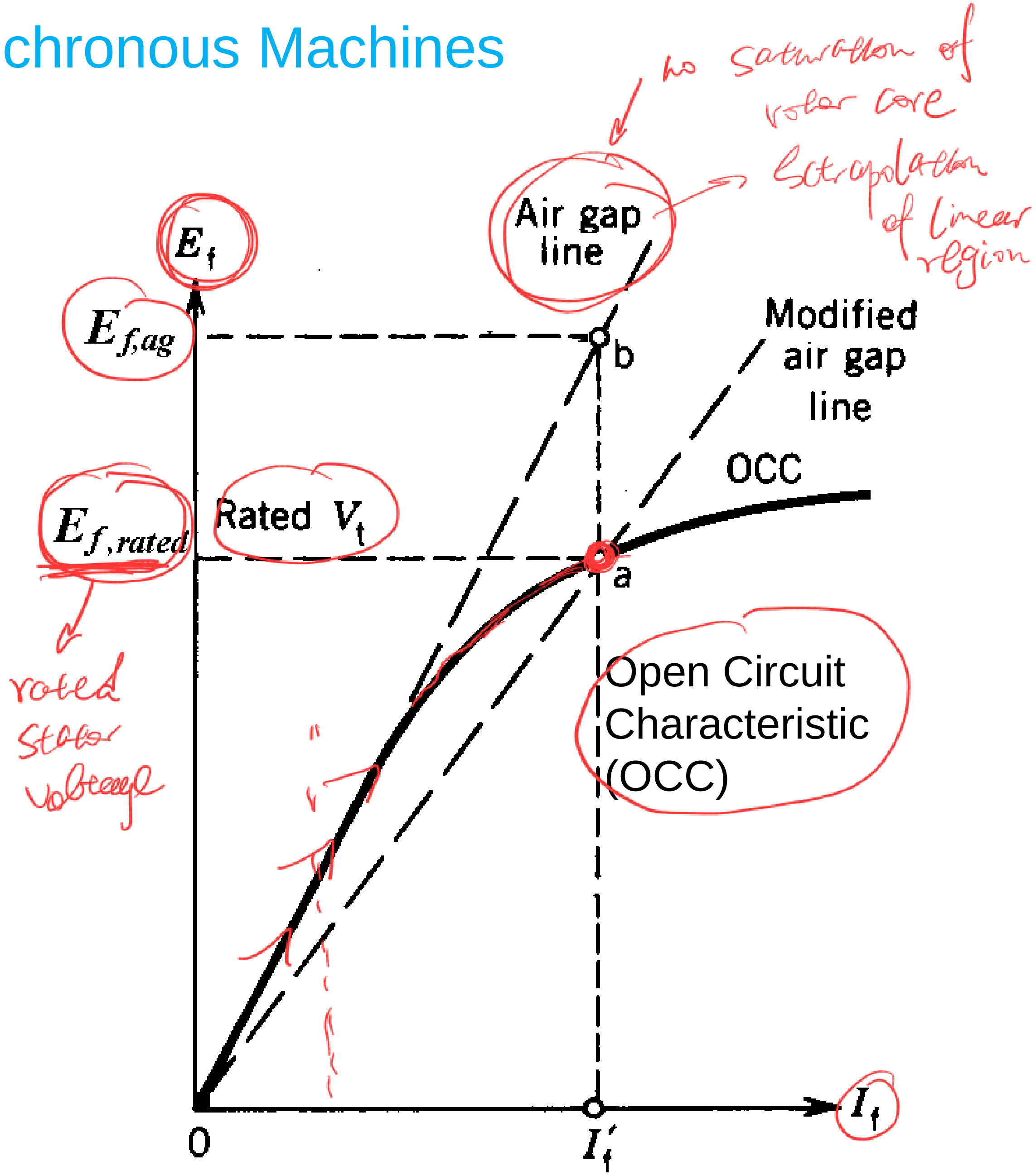
1. Use DC source to measure $R_s = \frac{V_{DC}}{2 I_{DC}}$ $R_f = \frac{V_{f\,DC}}{I_{f\,DC}}$
2. Do Open-Circuit Test (Slide 17)
3. Do Short Circuit Test (Slide 18)

need to combine these two results

Open-Circuit Test For Field-wound Synchronous Machines



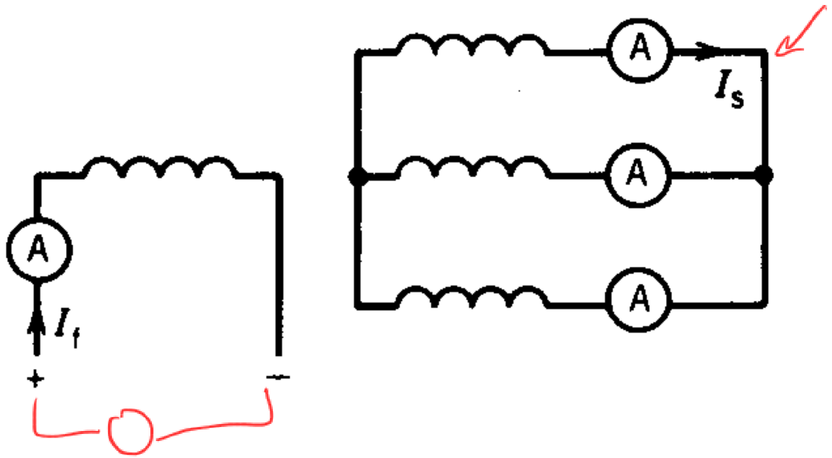
→ equal open circuit terminal voltage

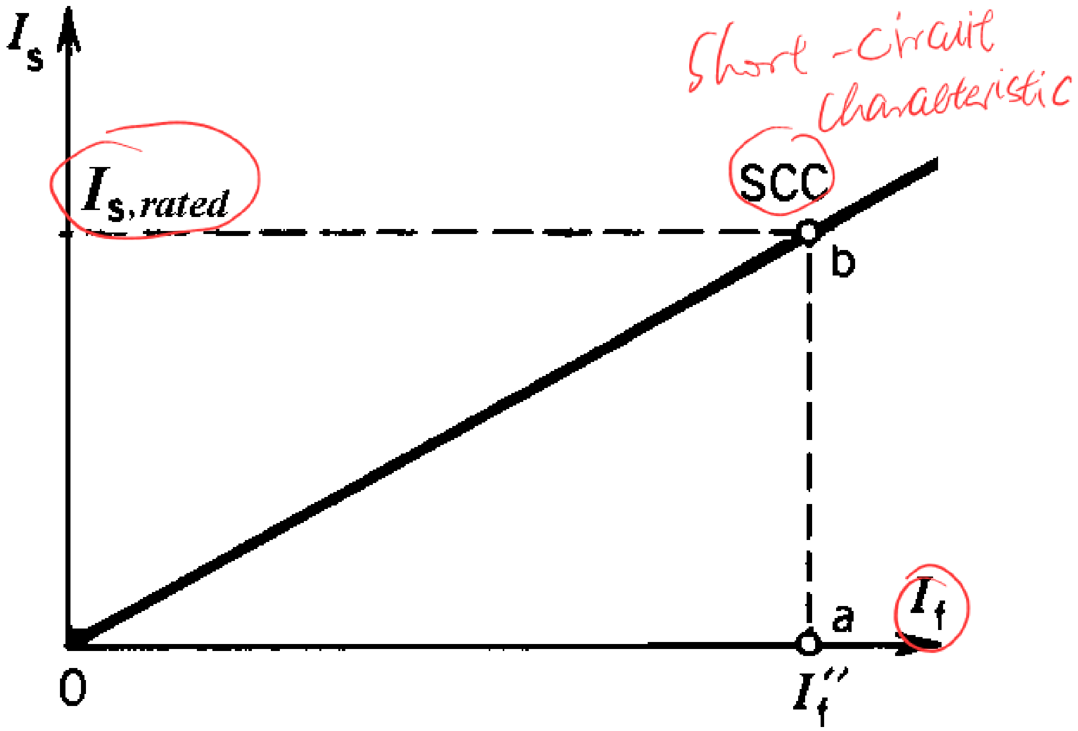


1. Use constant & nominal speed ω_r = const.
2. Vary field current (slowly)
3. Measure phase voltage → E_f
4. Measure field current → I_f

I_f' - Field current that results in rated (nominal) OC voltage

Short-Circuit Test For Field-wound Synchronous Machines





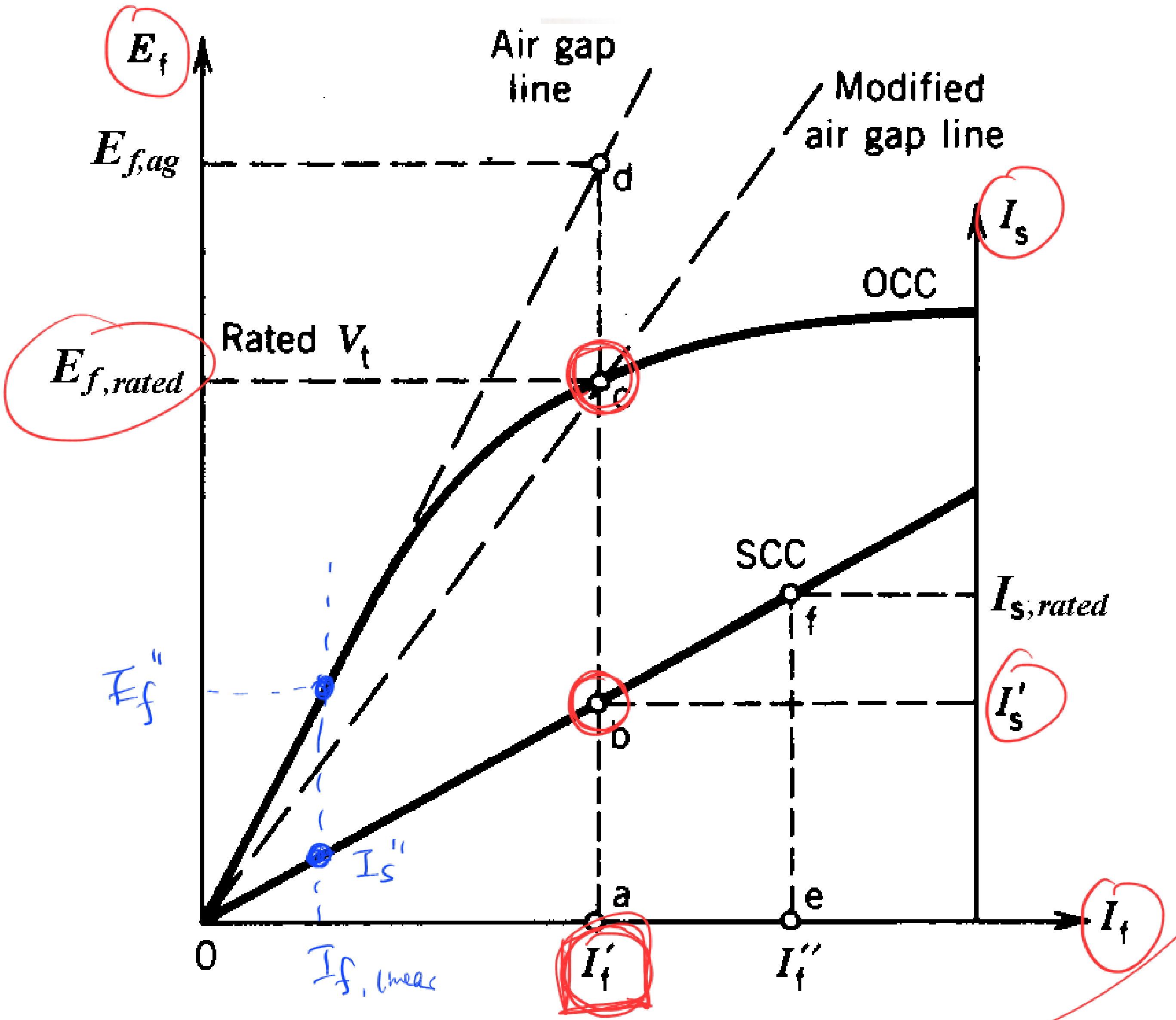
1. Use constant & nominal speed $\omega_r = \text{const.}$
2. Short the stator winding
3. Vary field current (slowly)
4. Measure phase current
5. Measure field current

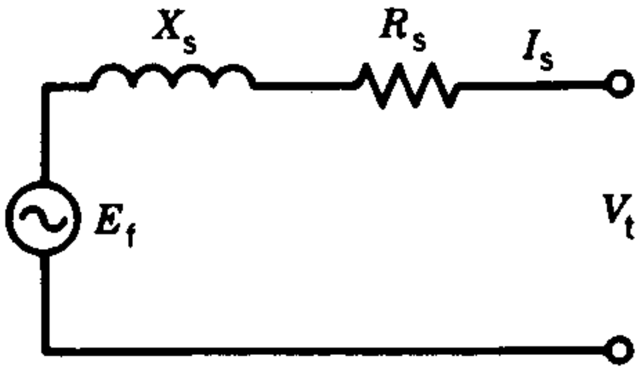
Do not exceed 125% of

$I_{s,rated}$ (nominal)

I_f'' - Field current that results in rated SC stator current

Combined Plot of OCC & SCC



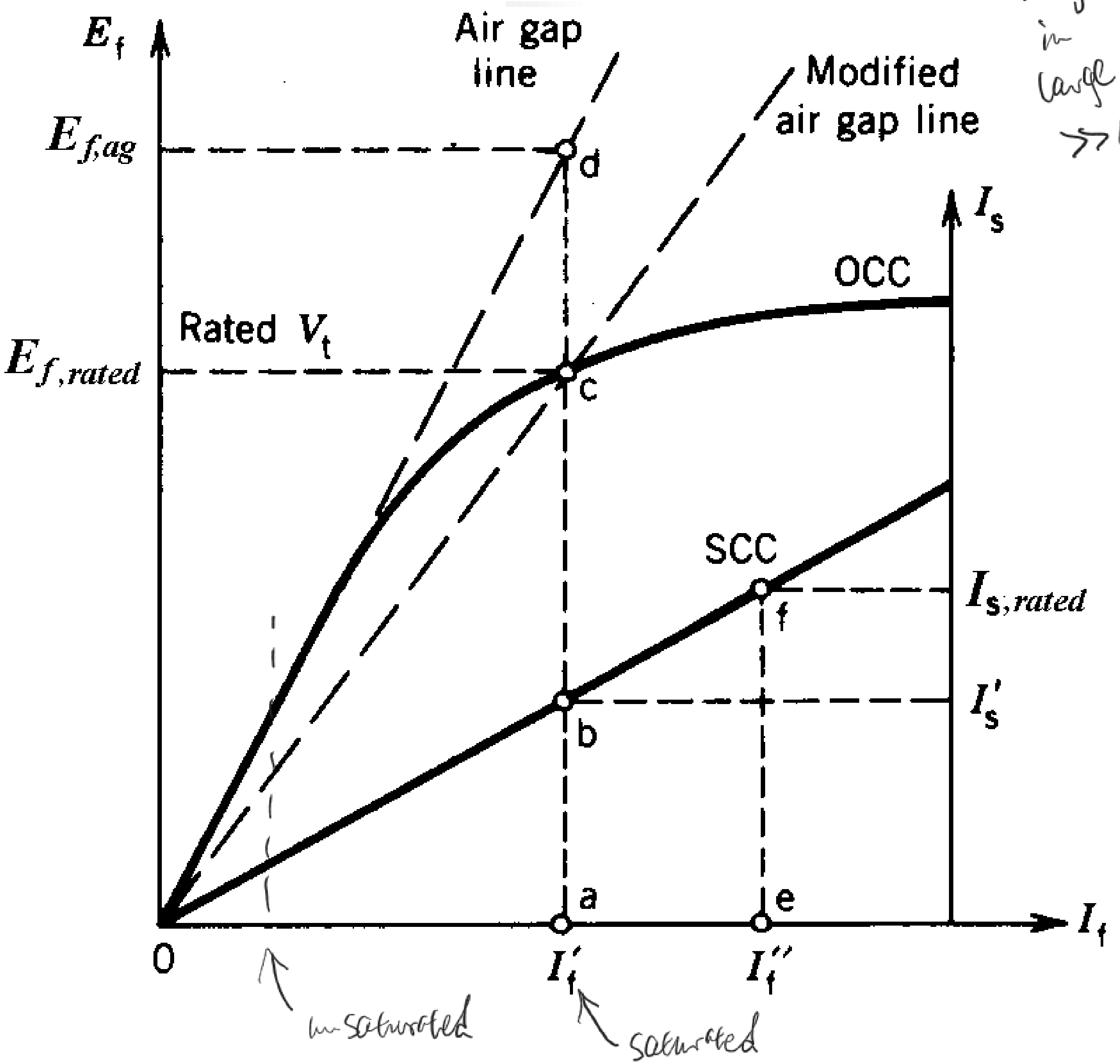


$$Z_{sat} = \frac{E_{f,rated}}{I_s'}$$

$$Z_{linear} = \frac{E_f''}{I_s''}$$

split to get R, X

Synchronous Reactance



neglect R_s in large SM >>MW

$$E_f = (R_s + jX_s)I_s = Z_s I_s$$

$$\approx X_s I_s \quad \text{(in terms of magnitude)}$$

Unsaturated Syn. Reactance:

$$Z_{s,unsat} = \frac{E_{f,ag}}{I'_s}$$

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

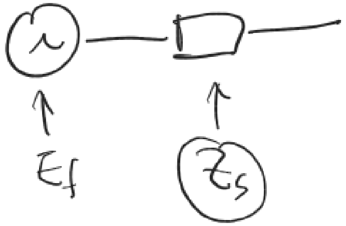
→ DC test

Saturated Syn. Reactance:

$$Z_{s,sat} = \frac{E_{f,rated}}{I'_s}$$

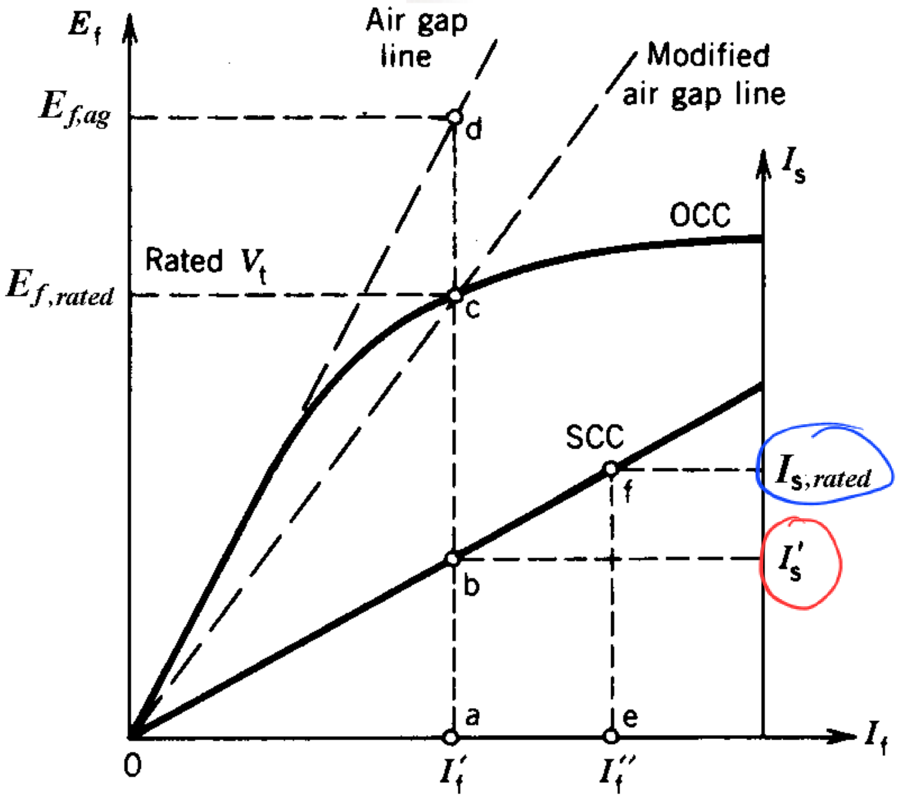
$$X_{s,sat} = \sqrt{Z_{s,sat}^2 - R_s^2}$$

Combined Plot of OCC & SCC



SCR larger → stronger the source

Short-Circuit Ratio (SCR) - ratio of steady-state SC current over the nominal (rated) current



$$SCR = \frac{I'_s}{I_{s,rated}} = \frac{I'_f}{I''_f} = $$

$$= \frac{E_{f,rated}}{I_{s,rated} Z_{s,sat}} = \frac{1}{Z^{pu}_{s,sat}} \approx \frac{1}{X^{pu}_{s,sat}}$$

Measure of strength of voltage source

Looking ahead…

- Continue **Module 6**