ELEC 342
Electromechanical Energy Conversion and Transmission

2025-26 Winter Term 2

Lecture 19

March 19, 2026

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Course Logistics

- Quiz 3 will take place on March 20
  - Detailed information already announced on Canvas
    - Beginning of tutorial and you will be given 20 minutes
    - Closed book and notes, calculators allowed
    - Coverage: Module 5

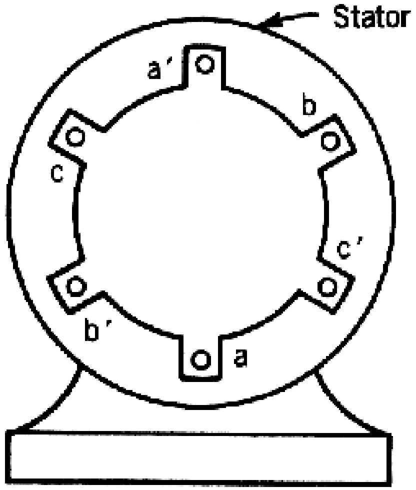
- Lab 4 posted and will take place next week

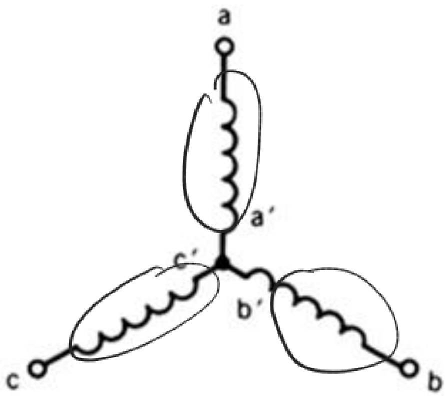
- SEI survey: March 28 – April 13

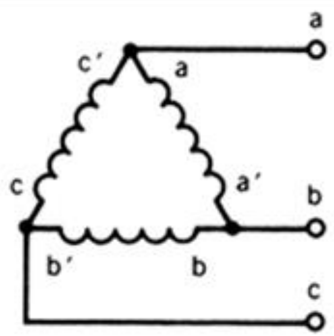
- Final exam: Apr. 19 @ 12 PM in IRC 4

Stator Windings

- ✓ A typical stator would have 3-phases, which may be Y or Δ connected
- ✓ Windings may have multiple sections with parallel and/or series connection
- ✓ The actual winding will be typically distributed as to better utilize stator volume and approximate smooth "sinusoidal" distribution





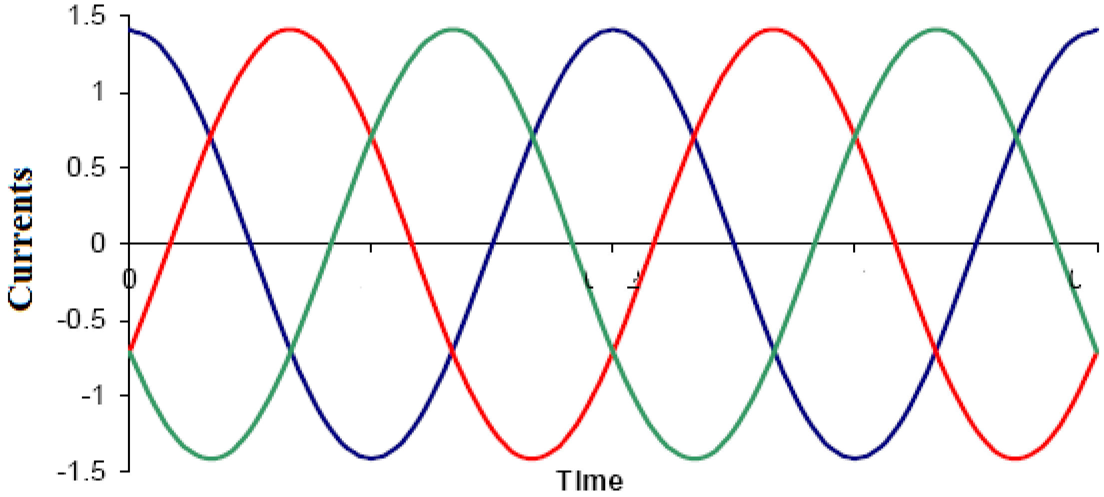


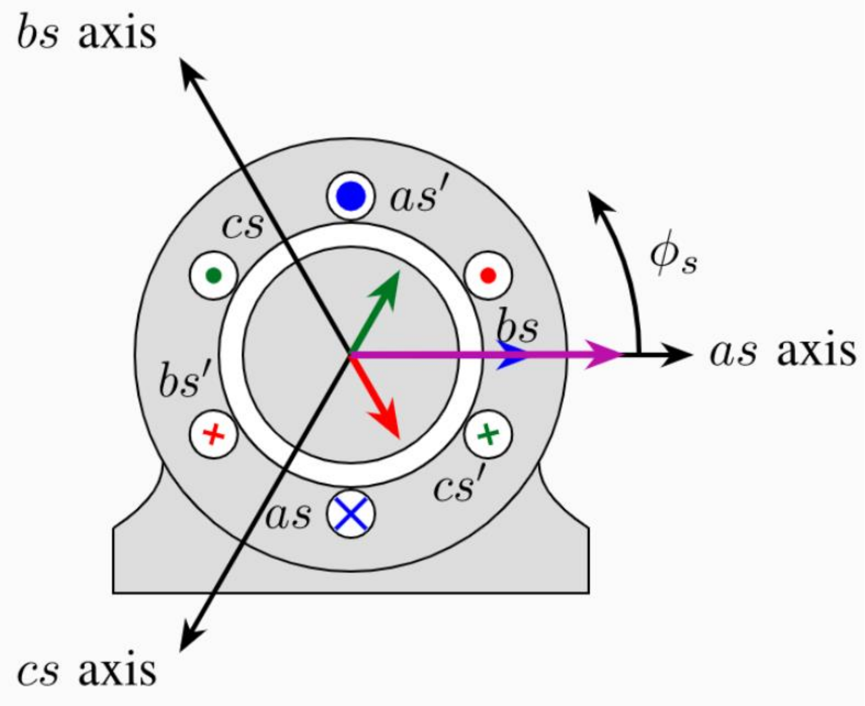
For simplicity, we can assume concentrated winding

Rotating Magnetic Field

➢ How to produce rotating magnetic field:

1. Given a balanced set of ac currents shifted in time
2. Apply these currents to windings symmetrically shifted in space ⇒ Produce vector $\mathbf{F}_s$ that
    - Has constant magnitude
    - Rotates in space $\rightsquigarrow$ $\omega_e t = \theta_e(t)$





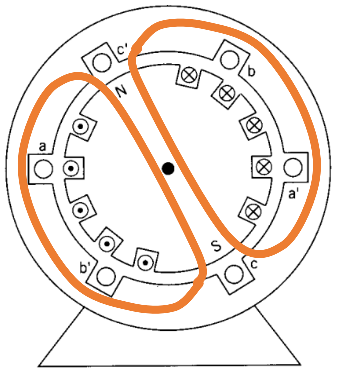
$$\mathbf{F}_s = (3/2)F_m\angle\theta_e$$

\# of phase

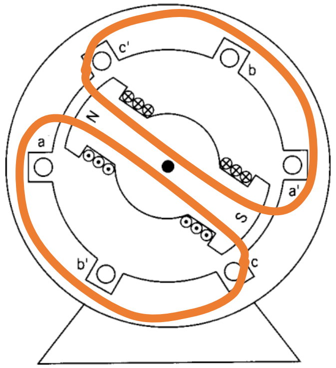
Poles & Speed in Syn. Machines

s = 0

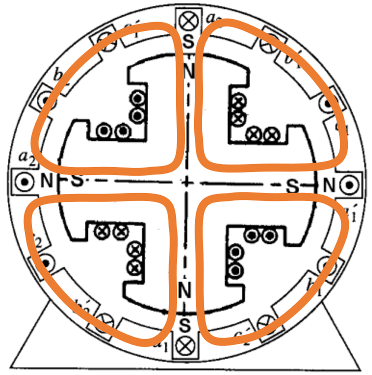
2-Pole Round Rotor



2-Pole Salient Rotor



4-Pole Salient Rotor



- **_P_-pole Stator System** (*P* – number of magnetic poles)

For North America f_e **= 60 Hz** $\omega_e = 2\pi \cdot f_e \text{ [rad/s]}$

Synchronous speed is 2/*P* of the electrical speed $\omega_{syn} = \frac{2}{P}\omega_e \text{ [rad/s]}$

Synchronous Speed in rev. per min. (RPM) $n_{syn} = \frac{30}{\pi}\omega_{syn} = 60\frac{2}{P} \cdot f_e$

✓ We can always "convert" a *P*-pole motor into an equivalent 2-pole motor using the *P*/2 factor !

$$\omega_r = \frac{P}{2}\omega_{rm} \qquad \theta_r = \frac{P}{2}\theta_{rm} \qquad T_e \propto \frac{P}{2}$$

P pole	n_{syn}	ω_{syn}
2	3600	120π
4	1800	60π
6	1200	40π
8	900	30π
~~15~~	~~??~~	~~??~~
64	112.5	3.75π

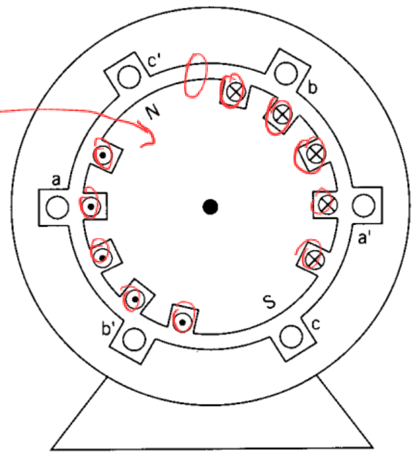
How many magnetic poles can we have? 2, 4, ~~15~~, 64…

Round Rotor Types → air gap constant → reluctance torque low

- **A typical round rotor has small number of magnetic poles**

2-Pole Round Rotor

rotor

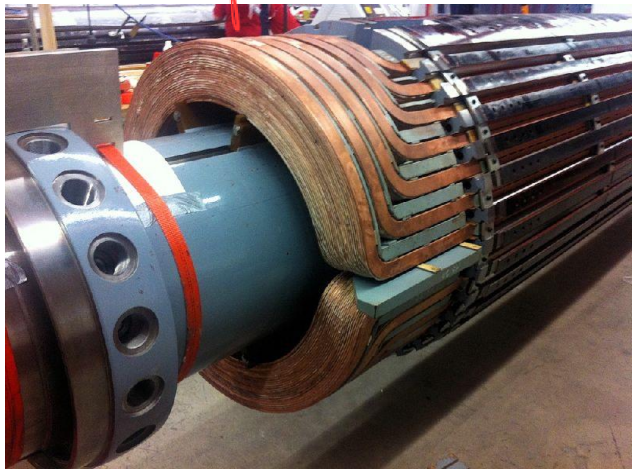


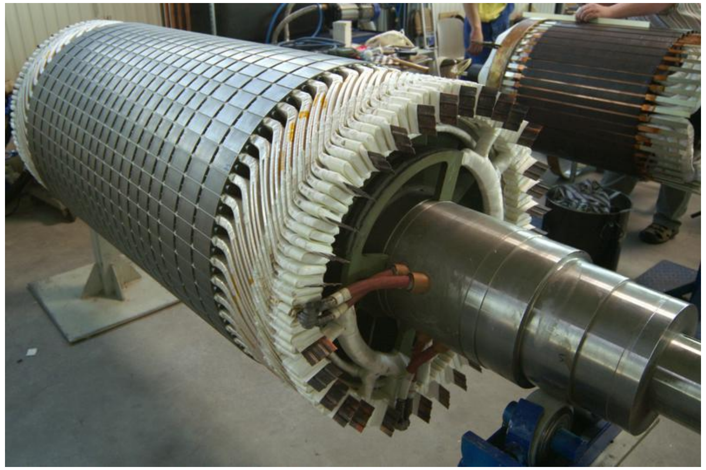
→ thermal power plant

① Harder to make

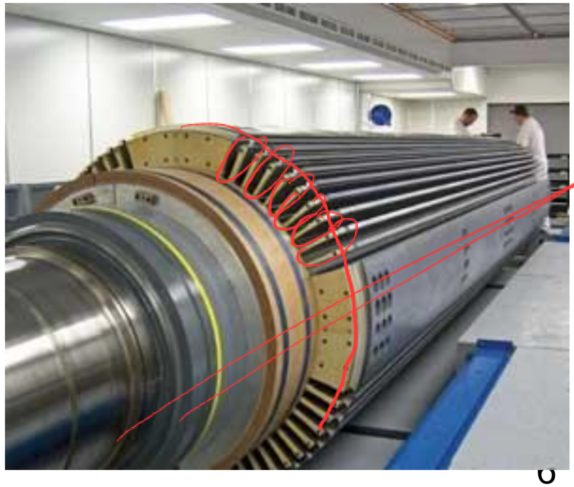
② Has smaller torque
↓
to increase torque
↓
make rotor longer (area ↑)

p = 2





4-Pole Rotor



Salient Rotor Types

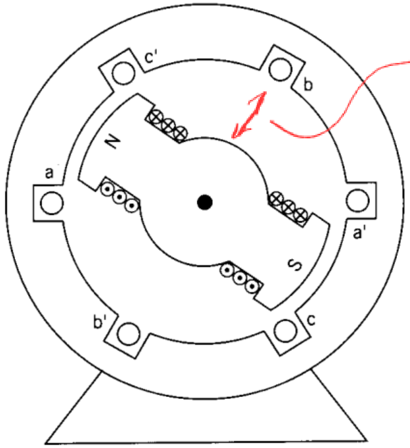
Typically used in low speed high torque applications

- A typical salient rotor may have more magnetic poles

stick it to core

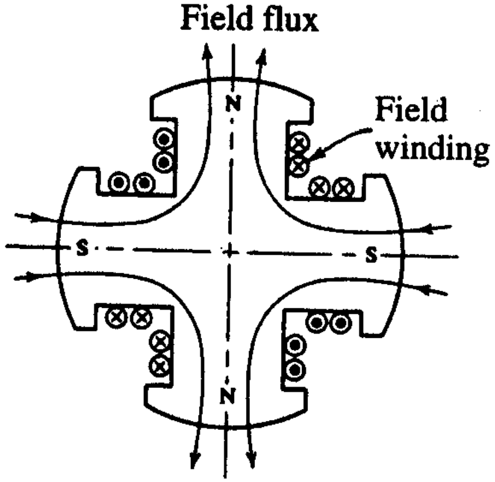
easier to make separate poles

2-Pole Salient Rotor

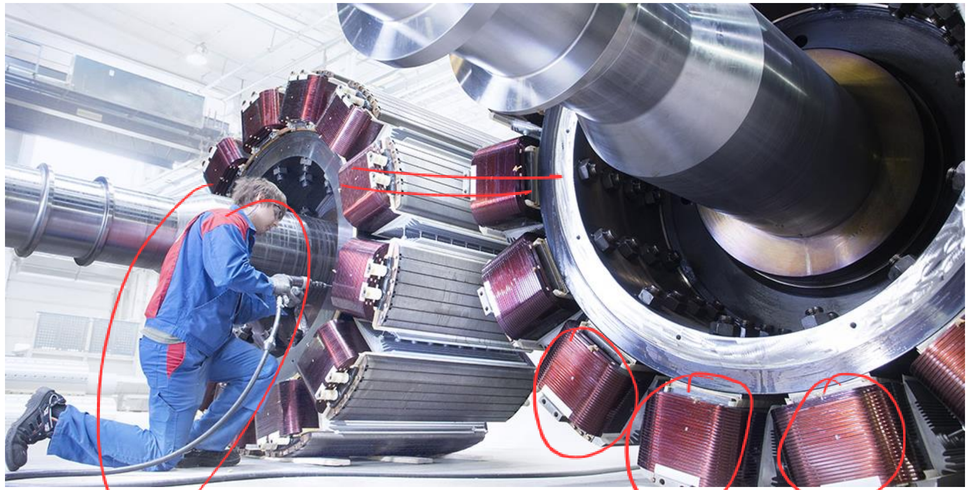


air gap varies, you get reluctance torque

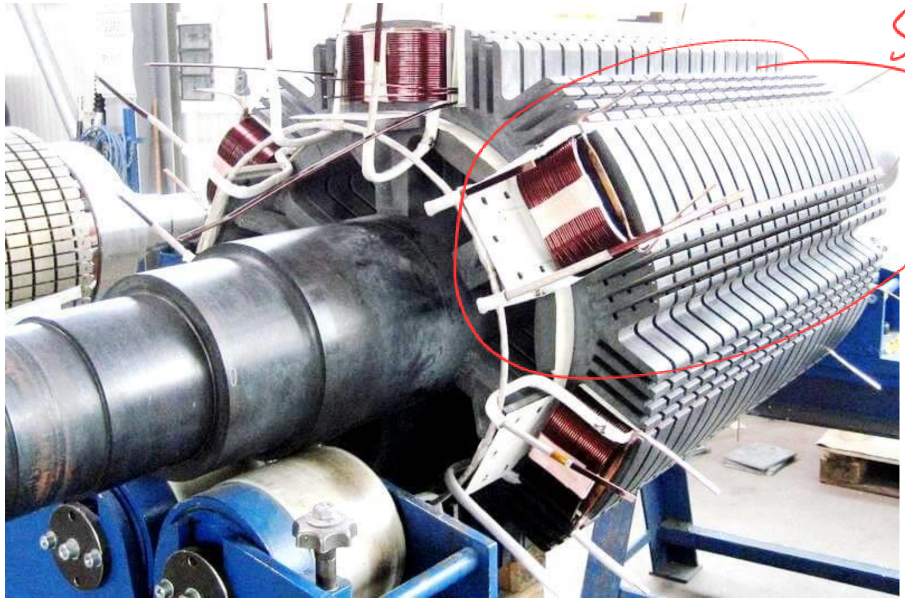
4-Pole Salient Rotor



Projecting out



attached



Short rotor

Rotor Types & Damper Windings

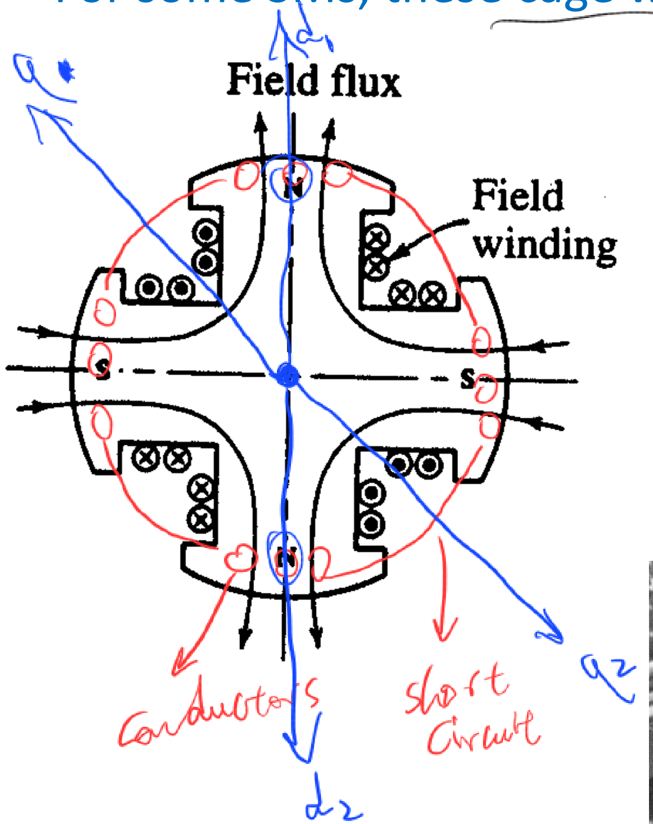
- Install additional winding (similar to squirrel-cage) to damp the rotor electromechanical oscillations during transients

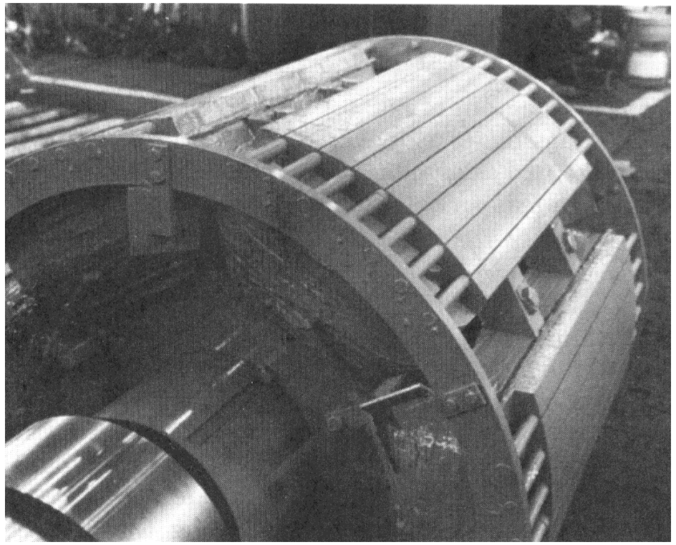
  develops opposing torque

- For some SMs, these cage winding may be used for starting

  ↳ from stall condition

  ↳ after start-up, then you supply field



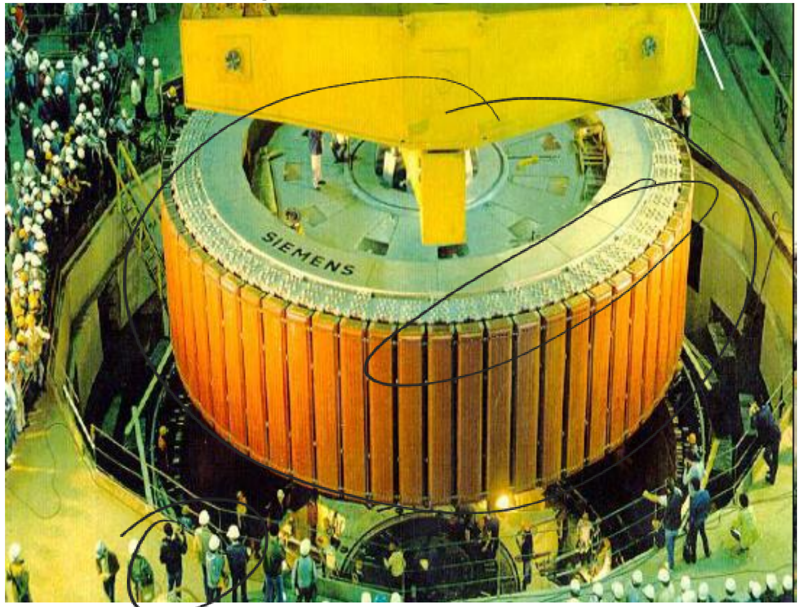


Poles & Speed in Syn. Machines

Speed $n_{syn} \propto \frac{2}{P}$ **Torque** $T_e \propto \frac{P}{2}$

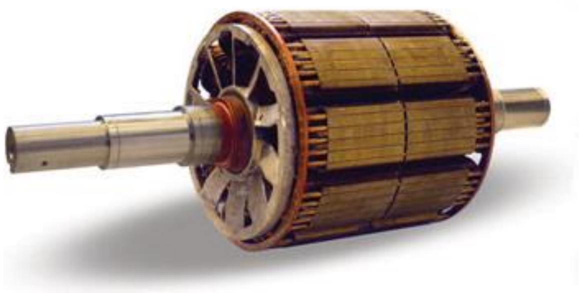
$\rightarrow$ 1 GW

823MVA Hydro Generator, Brazil



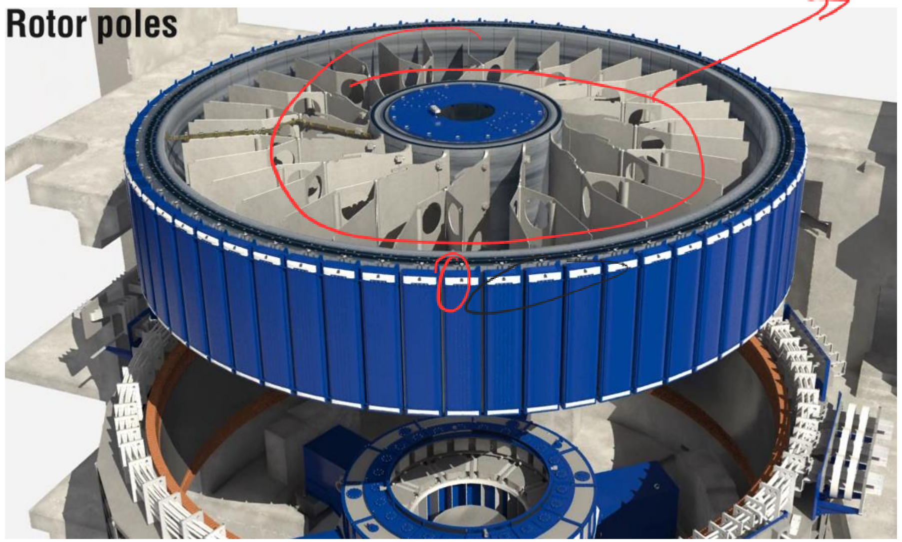
7500 HP, 16kV Syn. Motor

8-Pole Salient Rotor



no magnetic structure inside

64-Pole Salient Rotor Hydro Generator



Generation & Utilization of Electricity

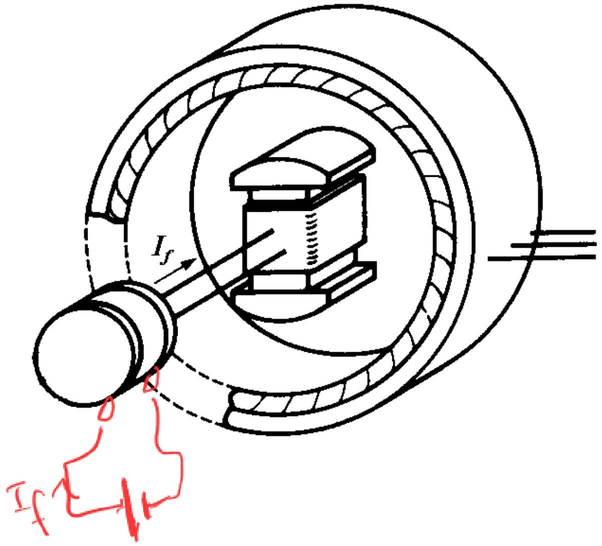
- Use low number of poles (e.g. 2, 4, 8, etc.) for high-speed (e.g. 3600 – 900 rpm) low torque applications
  - Steam & thermal turbine generators, high speed motors, etc.
- Use high number of poles (e.g. 64..) for low-speed (e.g. 112.5 rpm) high torque applications
  - Hydro generators, direct-drive wind generators, low speed motors, etc.

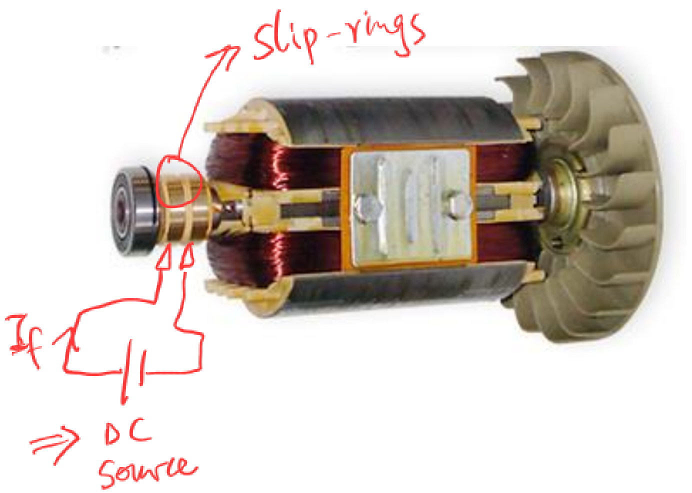
$\rightarrow$ No gearbox

Excitation – Establishing Rotor Field

- In order to establish the rotor magnetic field we need to pass DC current through the field winding

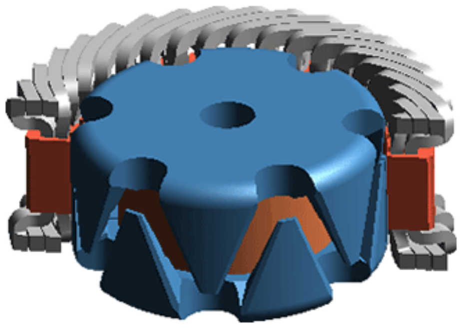
Use **Slip-Rings & Brushes** to energize the field winding from external DC source





Claw-Pole Rotor - typically used in automotive alternators

Two pieces clawed together



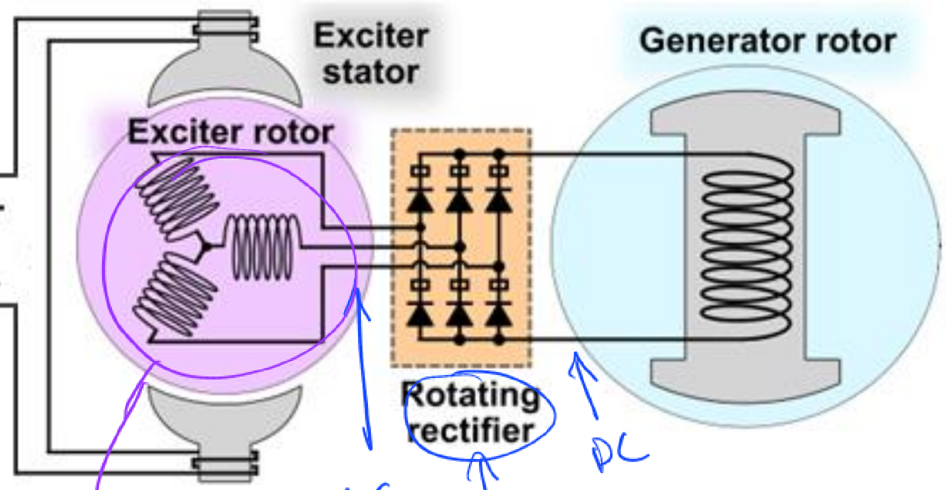
Brushless Excitation – Establishing Field → no brush + ring

✓ In order to establish the rotor field we need to pass DC current through the field winding

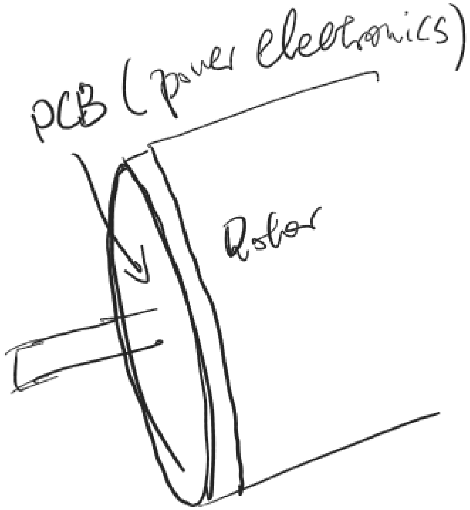
Brushless ⇒ Use internal (small) generator and rectifier mounted on the same shaft to produce DC inside the machine

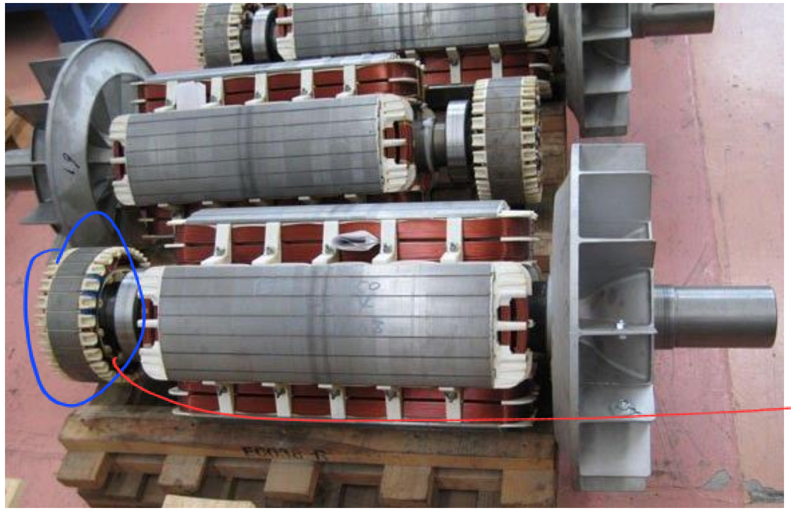
small machine on the same shaft

DC source



rotates in stationary magnetic field, so generates AC then converted to DC





Exciter

Brushless Excitation – Establishing Field

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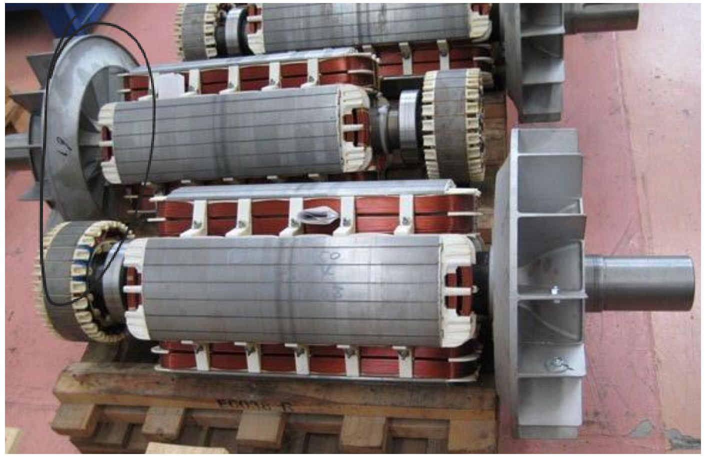
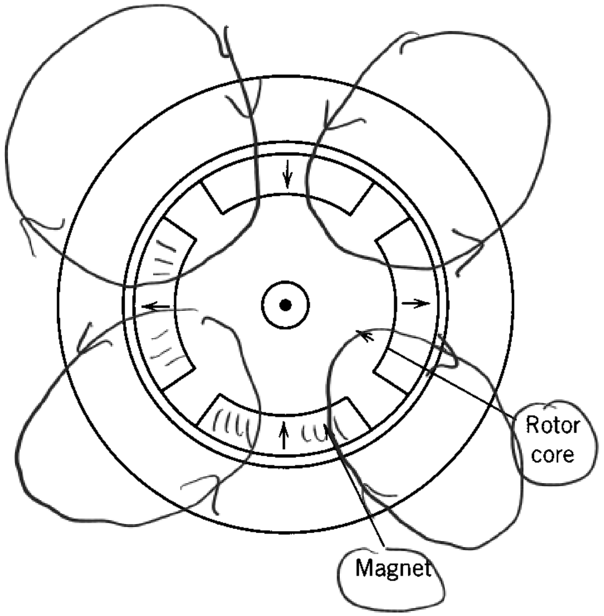


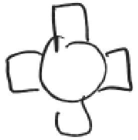
Exciter

Permanent Magnets (PM) Rotor Types

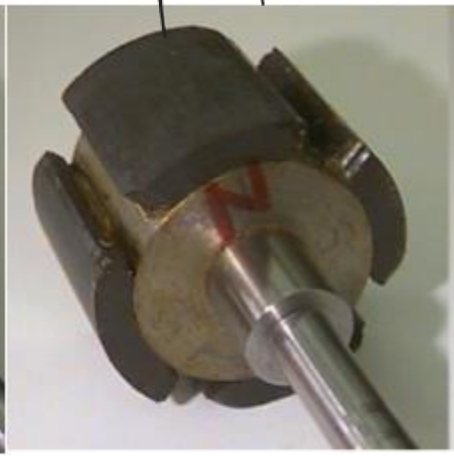
Use Permanent Magnets (PM) to establish the rotor field

Surface-Mounted PM Rotors





$p=2$ $p=4$ $p=8$



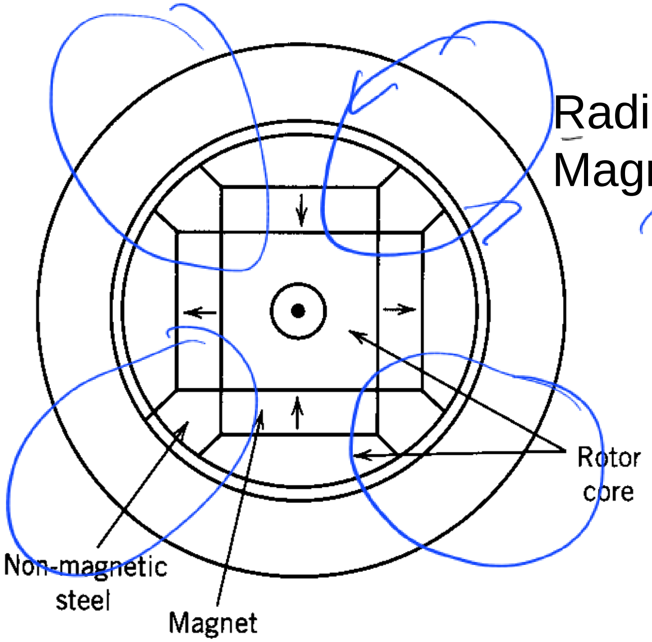
DCM inside out

$p=6$

Permanent Magnets (PM) Rotor Types

✓ **Use Permanent Magnets (PMs) to establish the rotor field**

❖ **Interior PM (IPM) Rotors**

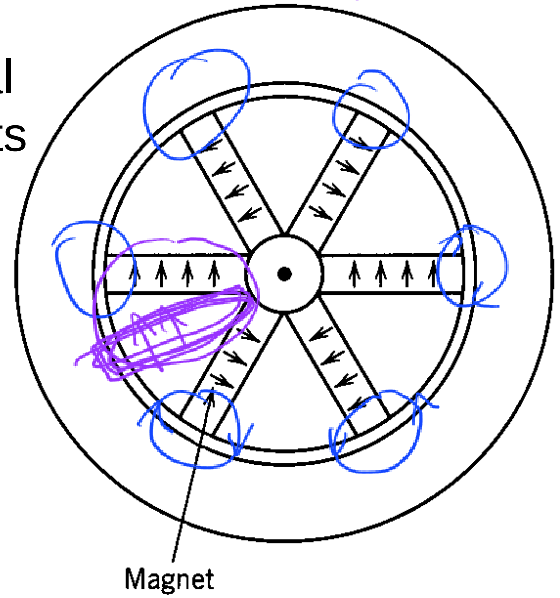


Radial Buried Magnets

$p=4$

Circumferential Buried Magnets

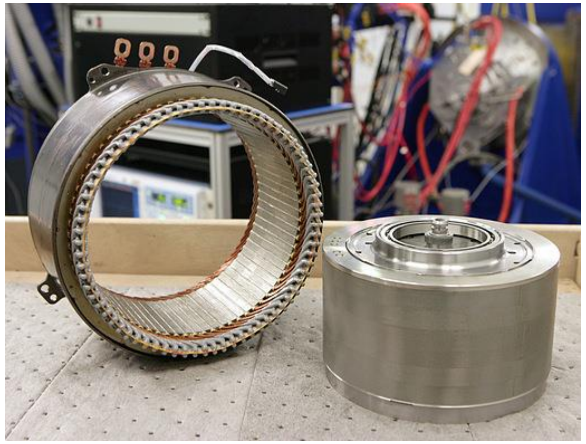
$p=6$



still 6 poles even if you insert 7 magnets

↓

one pole is larger than others



core

IPM (Interior Permanent Magnet)

Reluctance Rotor Types

→ Synchronous machines by principle of operation
→ no excitation + no magnets

Variable reluctance synchronous machines (RSM)

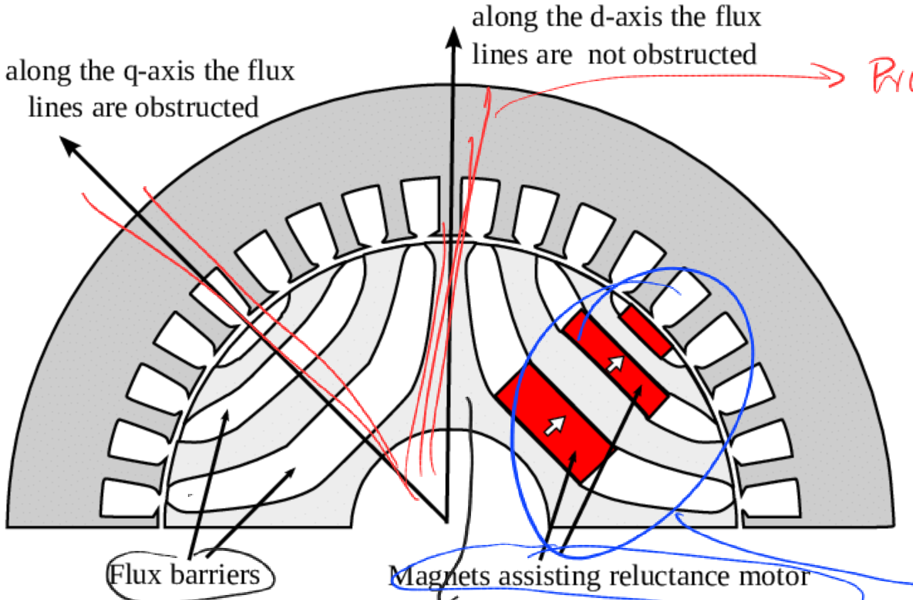
Use different materials and structures to establish rotor flux path with small and large reluctance

Stator same as SM/IM

Out running motor
↓
outside is rotor + spinning

→ rotor

Stator



→ Preferred path of flux

air or insulator

iron

→ Hybrid to get higher torque

- No winding on rotor, no magnet on rotor
- Just variable reluctance
- Simple to make, but low torque

Direct & Quadrature Axes → d-axis, q-axis

For now assume 2-Pole Round-Rotor

We can always "convert" a P-pole machine into an equivalent 2-pole machine using the $P/2$ factor

Equivalent 2-pole motor speed

Actual mechanical speed

$$\omega_r = \frac{P}{2}\,\omega_{rm}$$

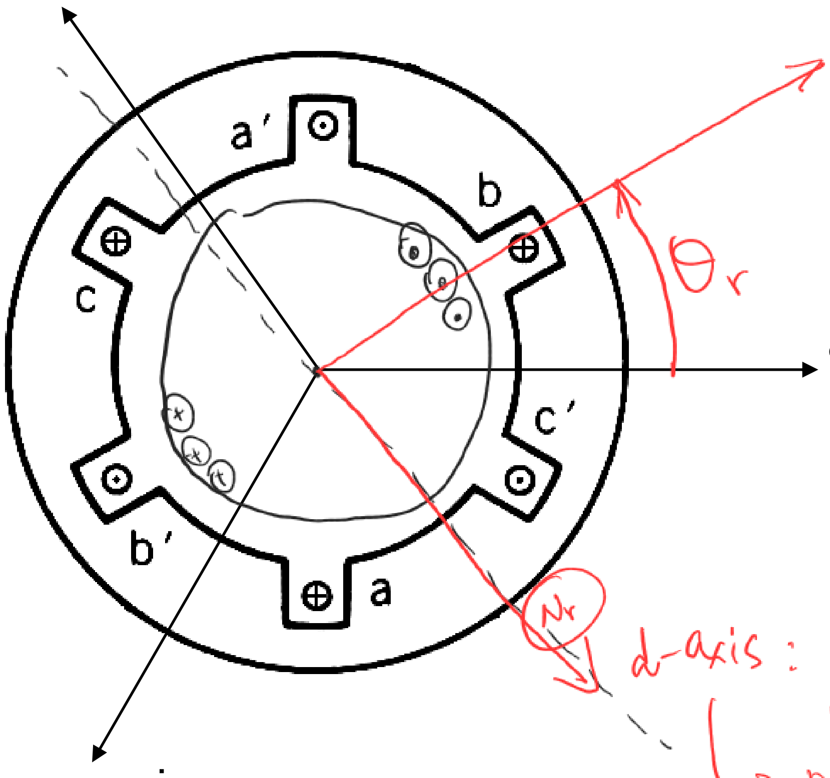
$$\theta_r = \frac{P}{2}\,\theta_{rm}$$

In steady-state:

dq-axis rotates @ speed

$$\omega_r = \omega_e$$

rotor freq   stator freq.



q-axis: ahead of d-axis (CCW)

→ evenly between 2 poles

2-pole: q is 90° ahead of d

4-pole: q is 45° ahead of d

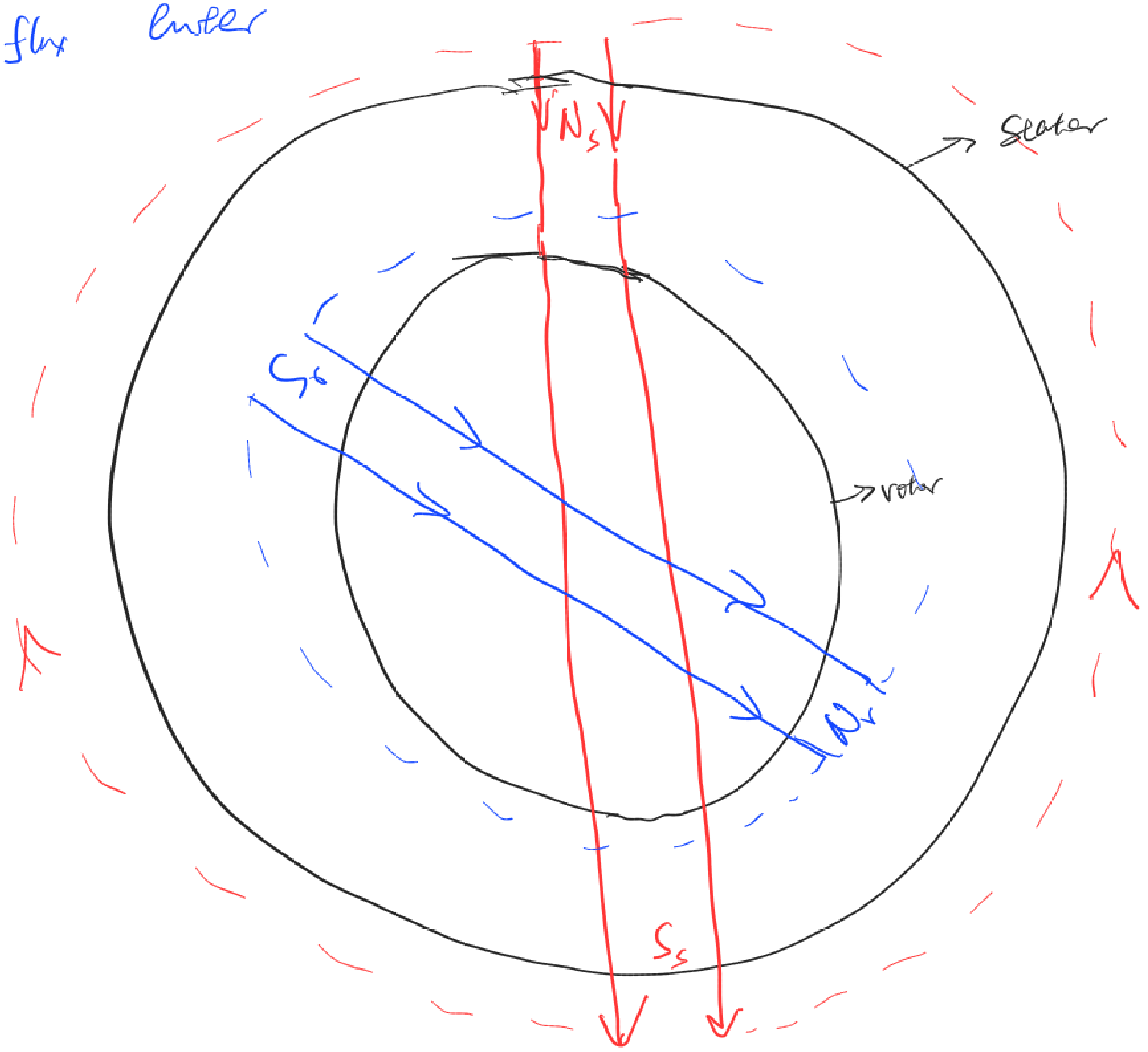
d-axis: flux produced by fielding winding

→ Direct magnetic axis of rotor pointing to N_r

Review: North & South Pole

North : flux exits

South : flux enter



Principle of Operation – Idle Mode

a) Assume no external torque $T_m = 0$

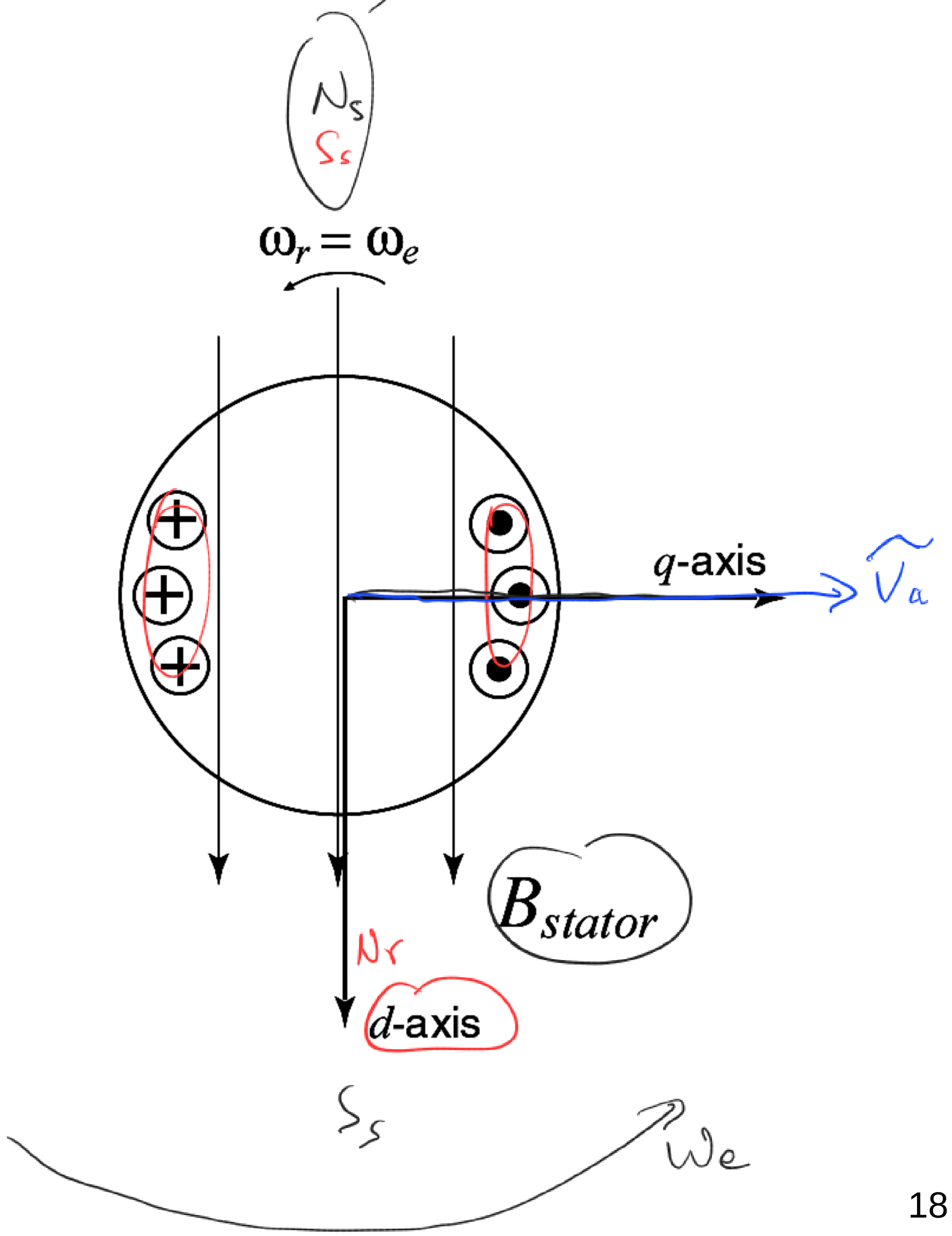
- Rotor poles are synchronized with the stator field
- Rotor poles are aligned with stator poles
- No torque produced $T_e = 0$

- Voltage V_a supplies stator

- Assume stator is inductive

- $\tilde{V}_a$ phasor points to right
  ↳ aligned with q-axis

aligned → no T_e produced



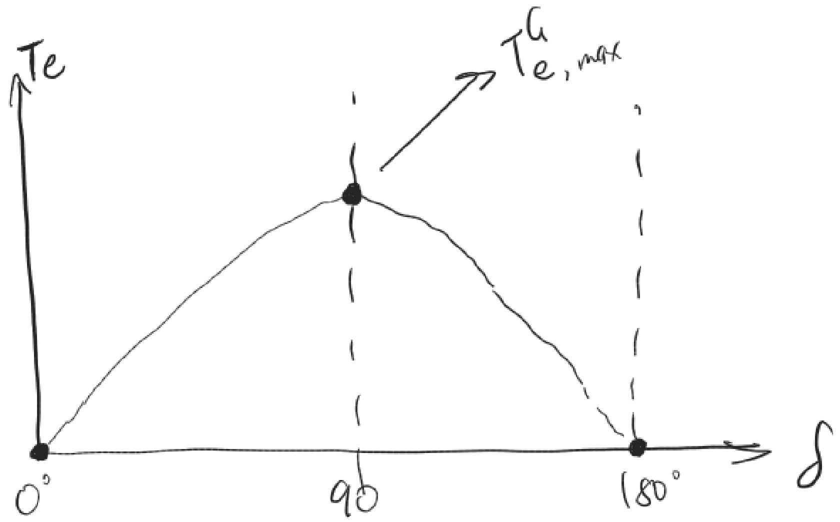
Principle of Operation - Generating

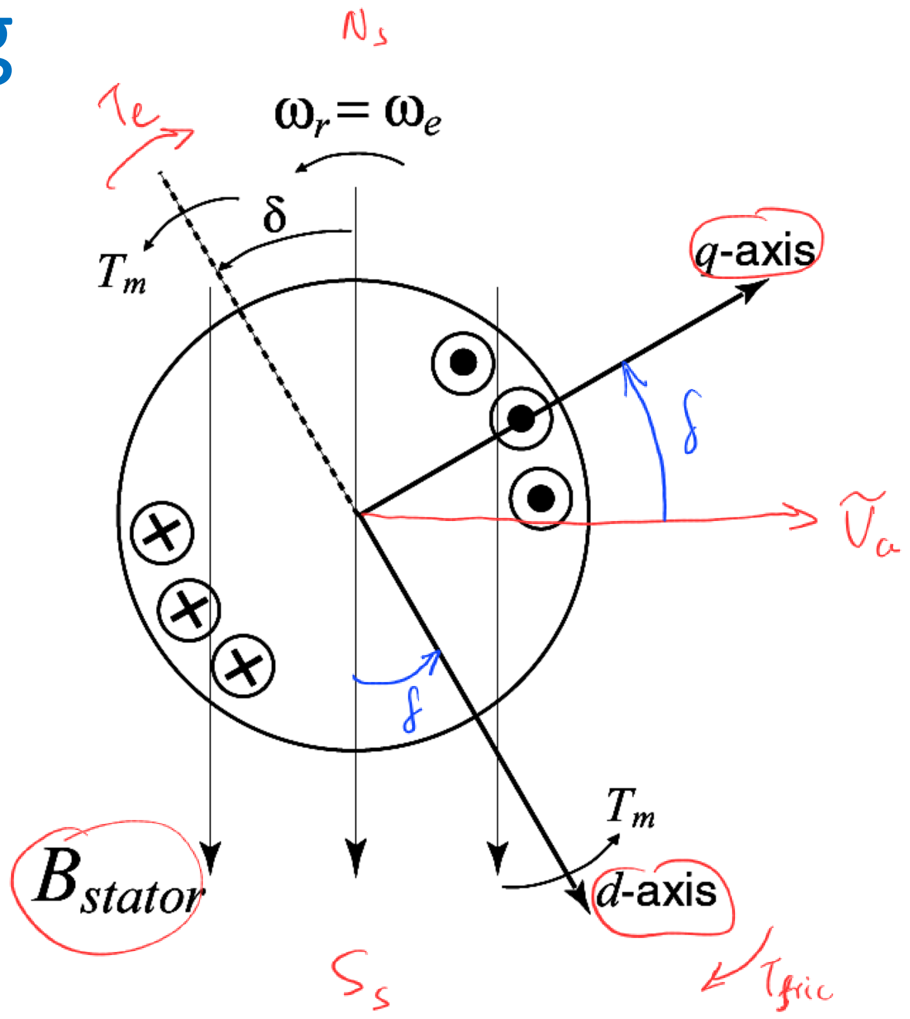
b) Apply external torque $T_m > 0$
in the direction of rotation

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

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

$\theta_r \rightarrow \int \omega_r \, dt$ $\qquad$ $\theta_e \rightarrow \int \omega_e \, dt$





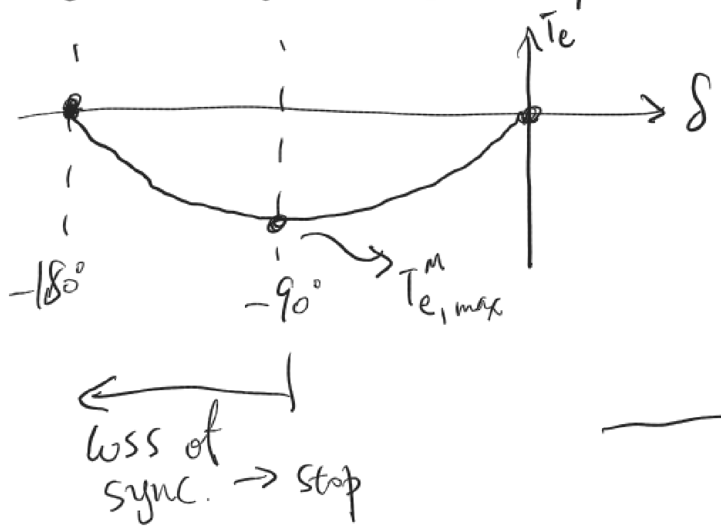
accelerate → run away (no opposing Te anymore) → avoid → lose sync.

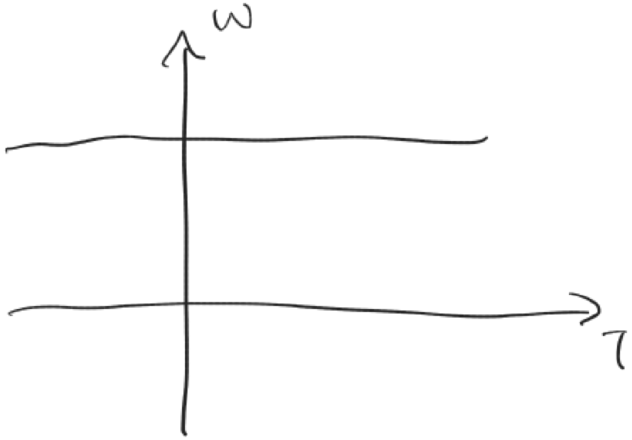
Principle of Operation - Motoring

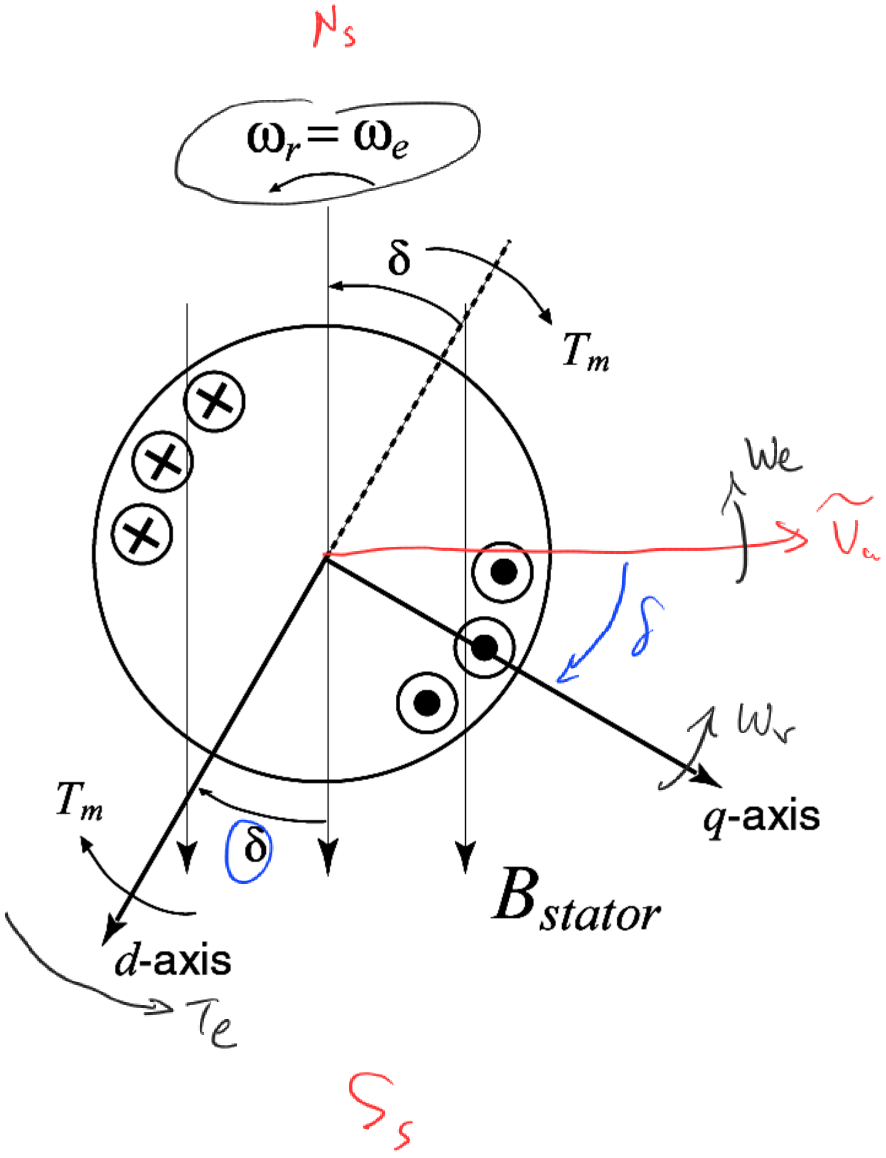
c) Apply external torque $T_m < 0$ in the direction opposite to rotation

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

$\delta = \theta_r - \theta_e < 0$







Looking ahead…

- Continue **Module 6**