ELEC 342
Electromechanical Energy Conversion and Transmission

2025-26 Winter Term 2

Lecture 14

March 3, 2026

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Course Logistics

- No tutorial this week
- Labs
  - See important announcement on Canvas: You must submit all 5 lab reports in order to take the final exam; also, labs cannot be re-weighted to the final
  - Lab 3 manual posted
- Assignments
  - One on Module 5
  - One on Module 6
- Quizzes
  - One on Module 5
  - One on Module 6

DC Machine

AC $\begin{cases} \text{Induction Machine} \\ \text{Synchronous Machine} \end{cases}$

Module 5: AC Induction Machines

Most commonly used AC motors in industrial applications

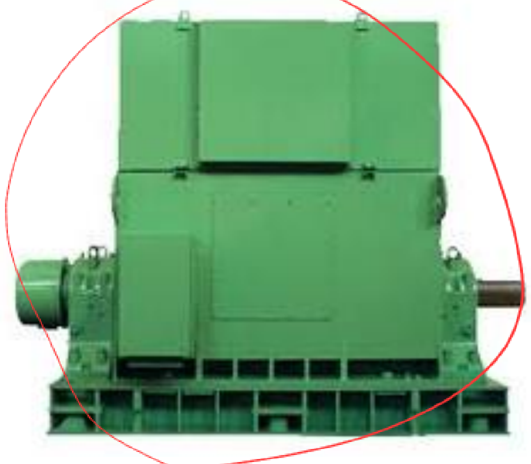
- *Efficient, Reliable*
- *Low maintenance*
- *Inexpensive to produce*
- *Often used with power-electronic drives*

Objectives & important concepts

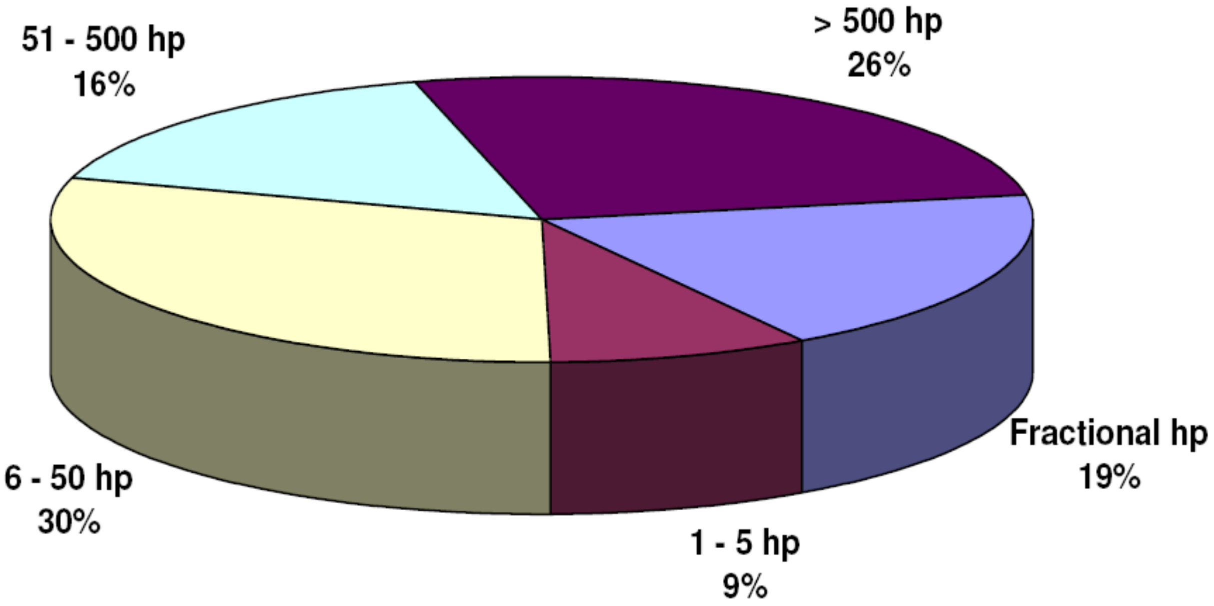
- Role and applications of induction machines
- Types and construction of typical induction machines
- Concept of rotating magnetic field → applies to all AC machines
- Multi-pole (*P*-pole) stator system
- Speeds (electrical, synchronous, mechanical, etc.)
- Concept of slip and slip frequency
- Principle of operation (motor / generator)
- Steady state equivalent circuits, determination of parameters, and application for engineering calculations
- Power conversion & development of electromagnetic torque
- Torque-speed characteristic, regions / modes of operation
- Effect of rotor bars design & NEMA Classes
- Basic principle of variable frequency drives (VFDs) & speed control

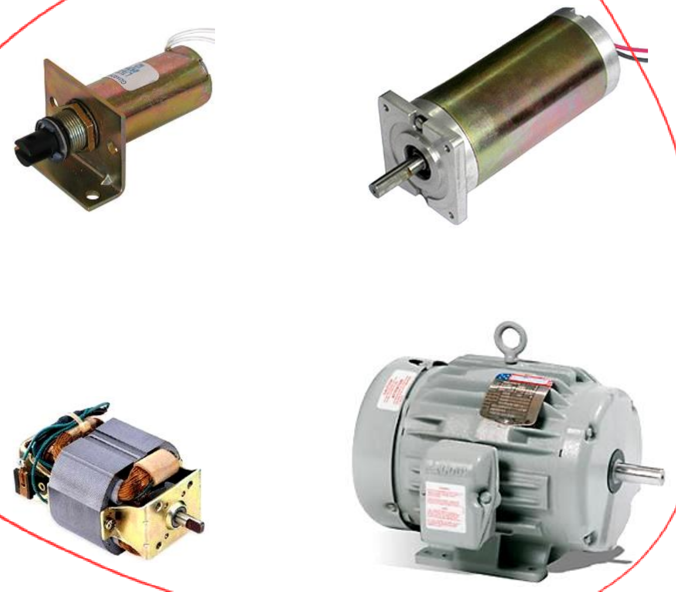
- Must read **Chapter 5**

Electrical Motors & Generators



- ❖ Electromechanical Energy Conversion Devices
  - – Predominant way of generating and consuming electrical energy
- ❖ Electrical Energy Generation
  - – Almost all electricity produced in BC (10 ~12GW) is produced by Synchronous Generators
- ❖ Electrical Energy Utilization
  - – About 65% of all electricity is consumed by motors: mostly induction, less synchronous, etc.
  - – For industry it is about 85%





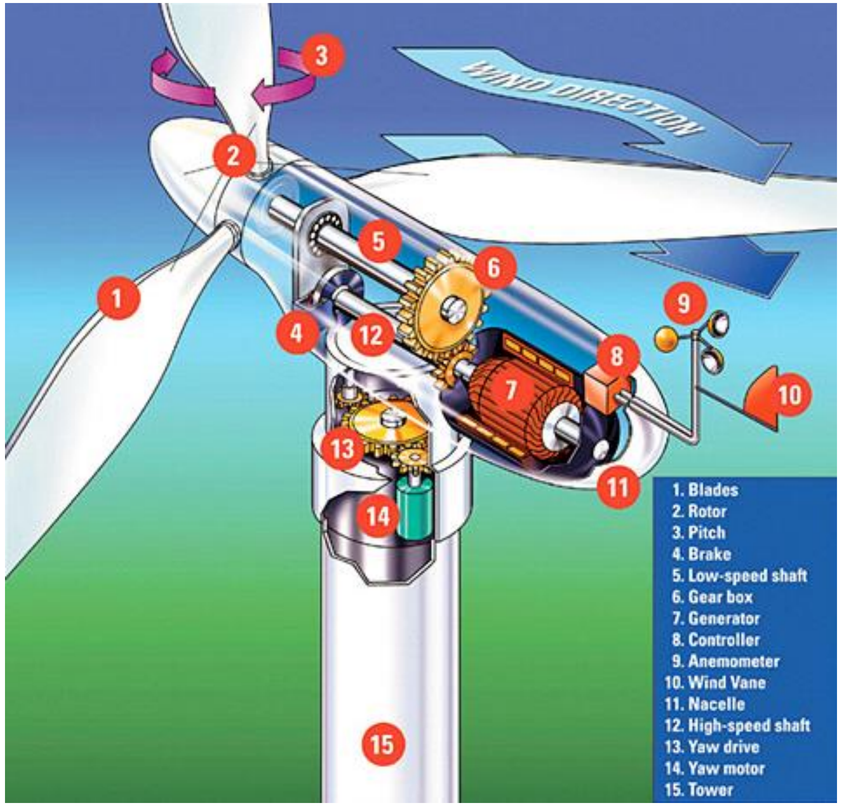
Induction Motors in Industry

Conveyor belt

Drills

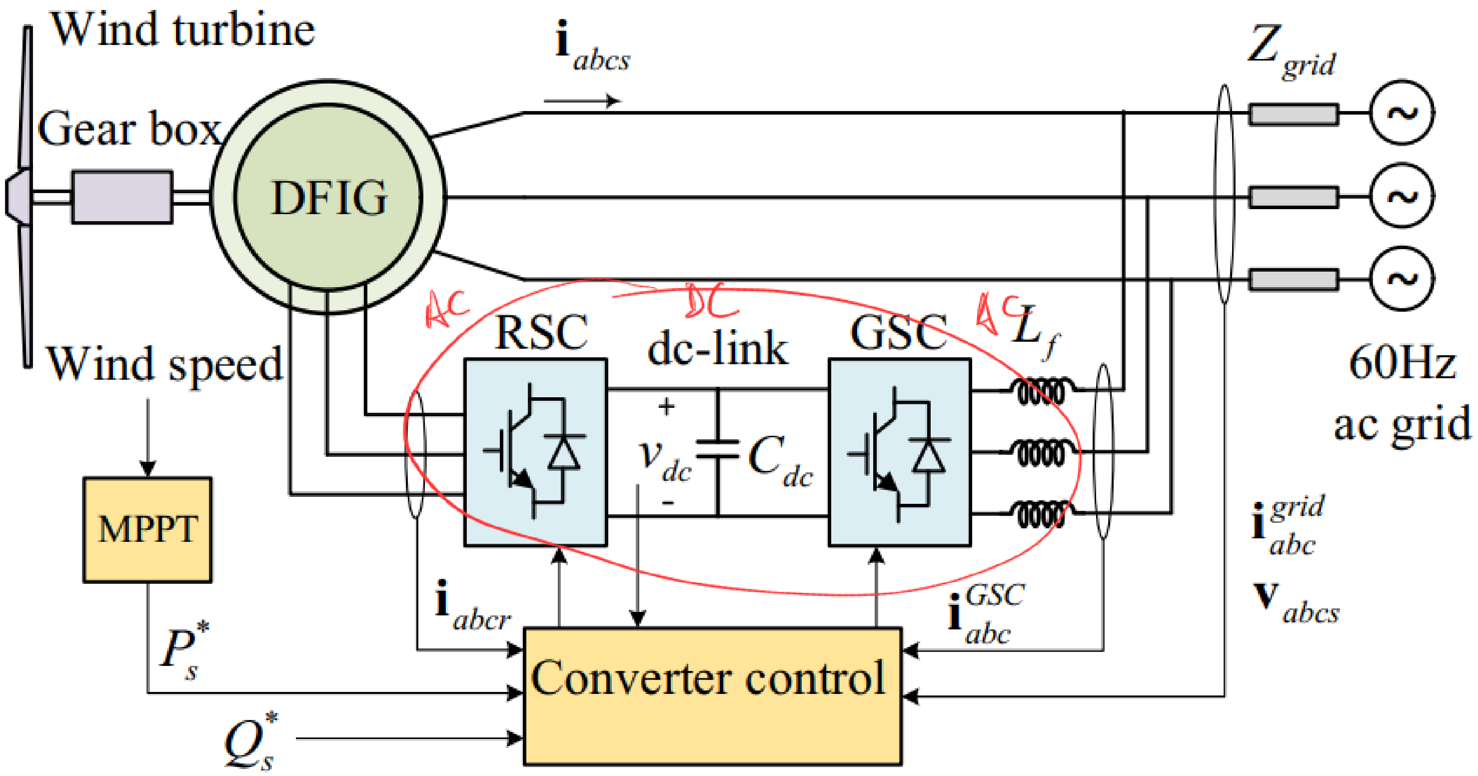
Cranes

Induction Generators



- Range from 1kW to 2MW
- Speed of the shaft changes with wind
- **Efficient, Reliable, Low maintenance**
- Often used with power electronic converters

Doubly-Fed Induction Generator (DFIG)



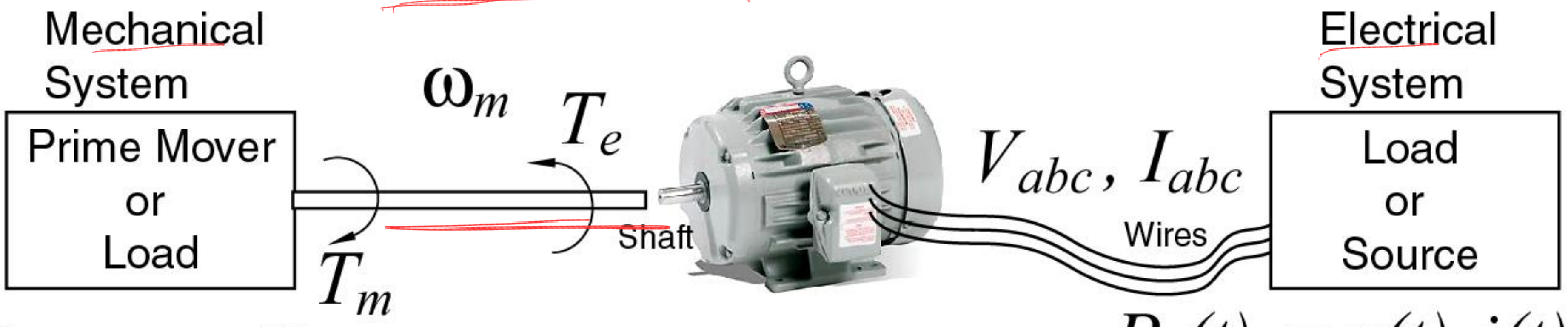
- The rotor has an actual winding which is accessed through slip-rings
- Stator is directly connected to the 3-phase grid
- Rotor voltages & frequency are controlled by Rotor-Side Converter (RSC)
- DC-link voltage is controlled by Grid-Side Converter (GSC)
- Maximum Power Point tracking control is typically implemented to maximize generation of renewable energy at given wind conditions
- **Mechanical/Electrical/Control expertise is needed**

Electromechanical Energy Conversion

Coupling field

Mechanical System (Prime Mover, Turbine, etc.) or (Load, plant) ⟷ Mechanical Energy ⟷ Conversion Device ⟷ Electrical Energy ⟷ Electrical System (Transmission, load, etc.) or (Substation, feeder, source, etc.)

Power Flow => Generator



$$P_m = \omega_m * T_m \qquad P_e(t) = v(t) * i(t)$$

Motor <= Power Flow

Can the energy flow in both directions in the same device? Yes

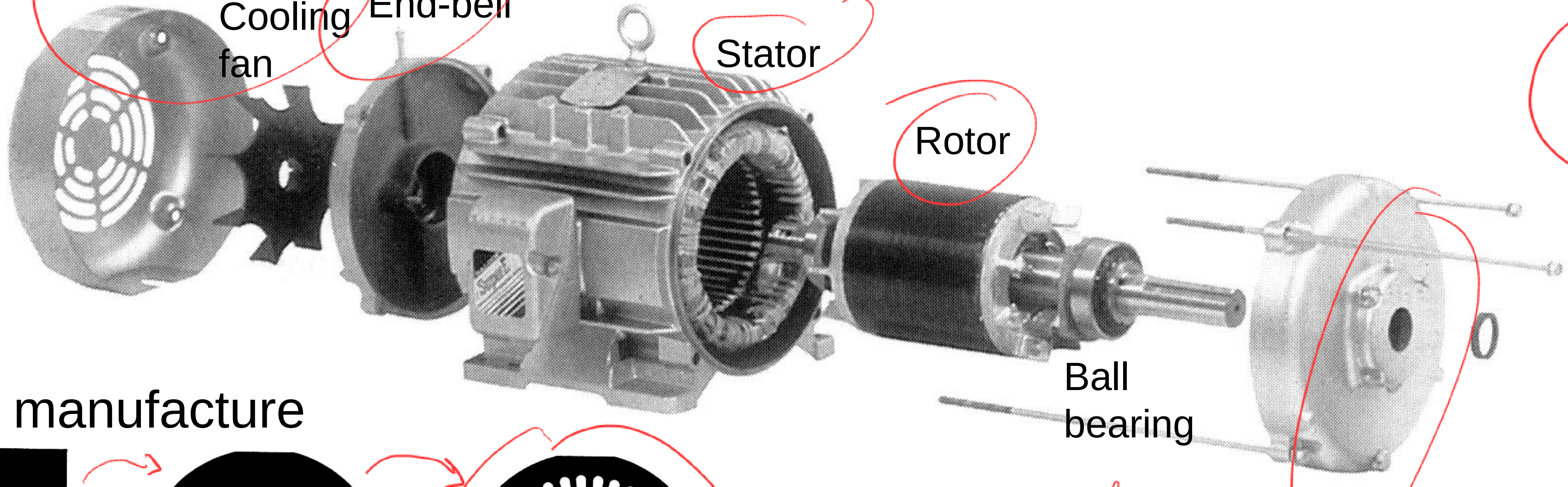
Can the energy flow into the device from both sides? Yes, only for a short time

Can the energy flow out of the device from both ends? Yes

What is inside that devices that can store energy? Coupling magnetic field, inertia (mechanical)

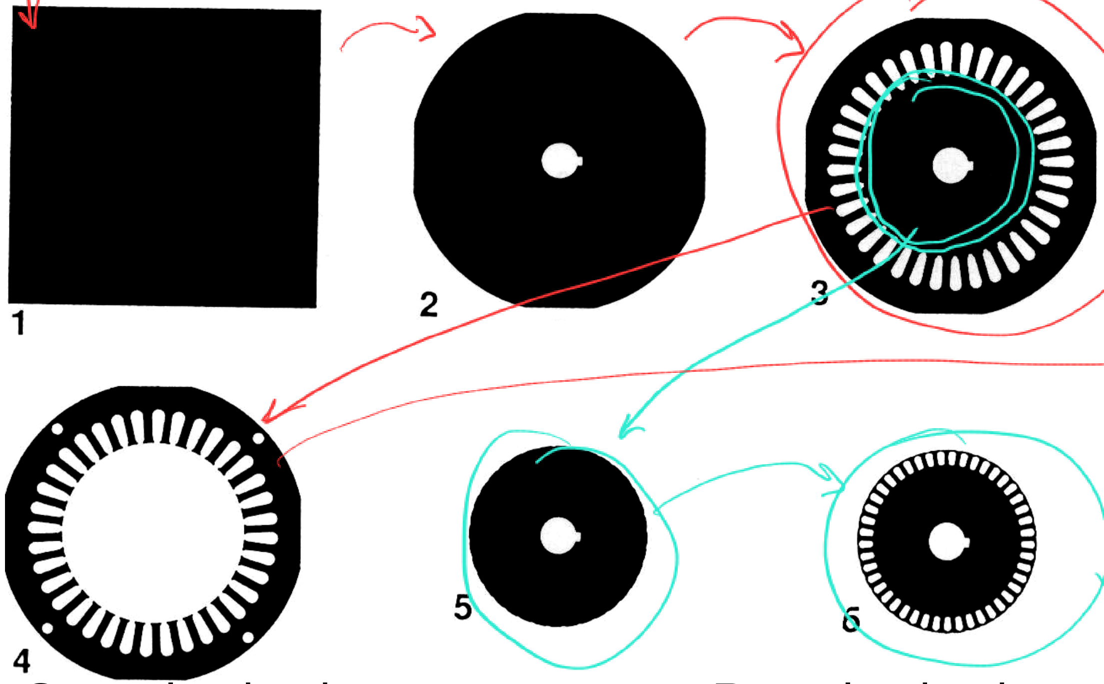
How does the energy gets converted? $\frac{dw}{dt} = f$

Construction of a Typical IM



Top view

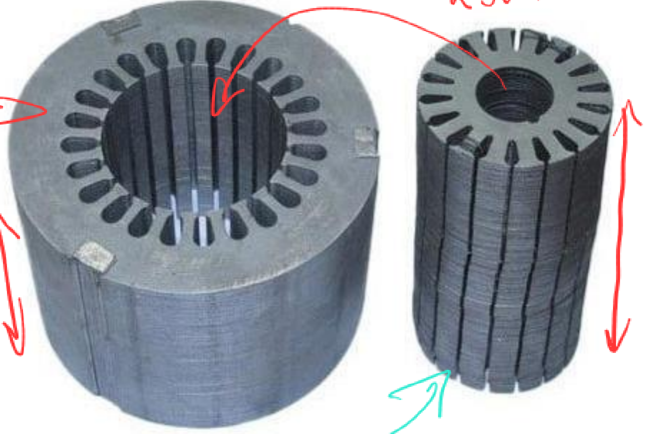
Easy to manufacture



Stator lamination

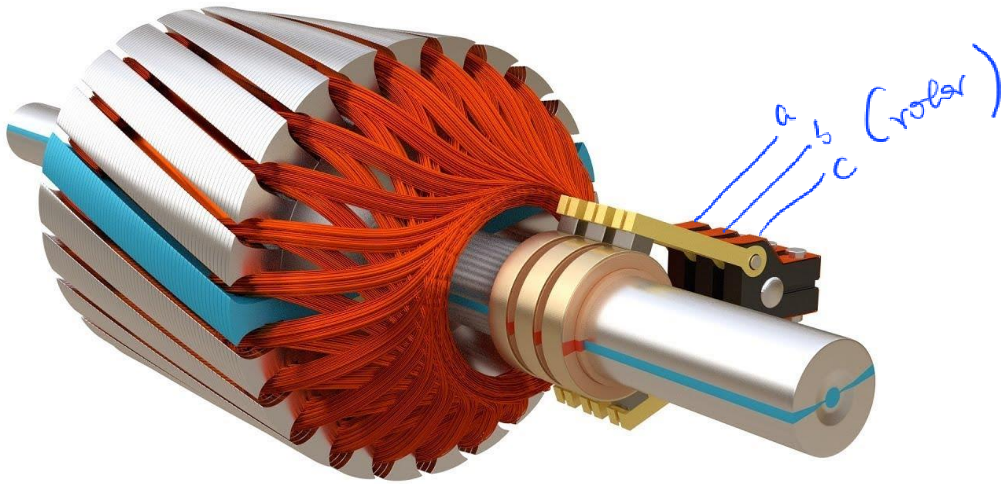
Rotor lamination

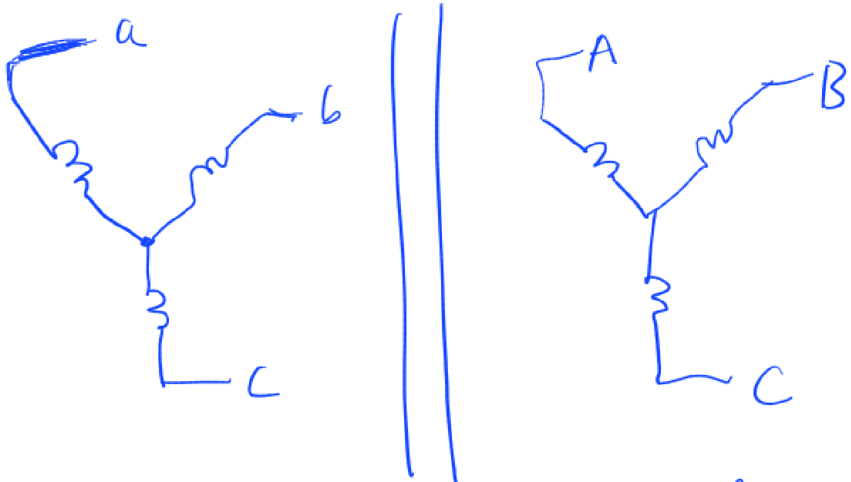
Simple manufacturing
No material wasted
Lamination: reduce losses



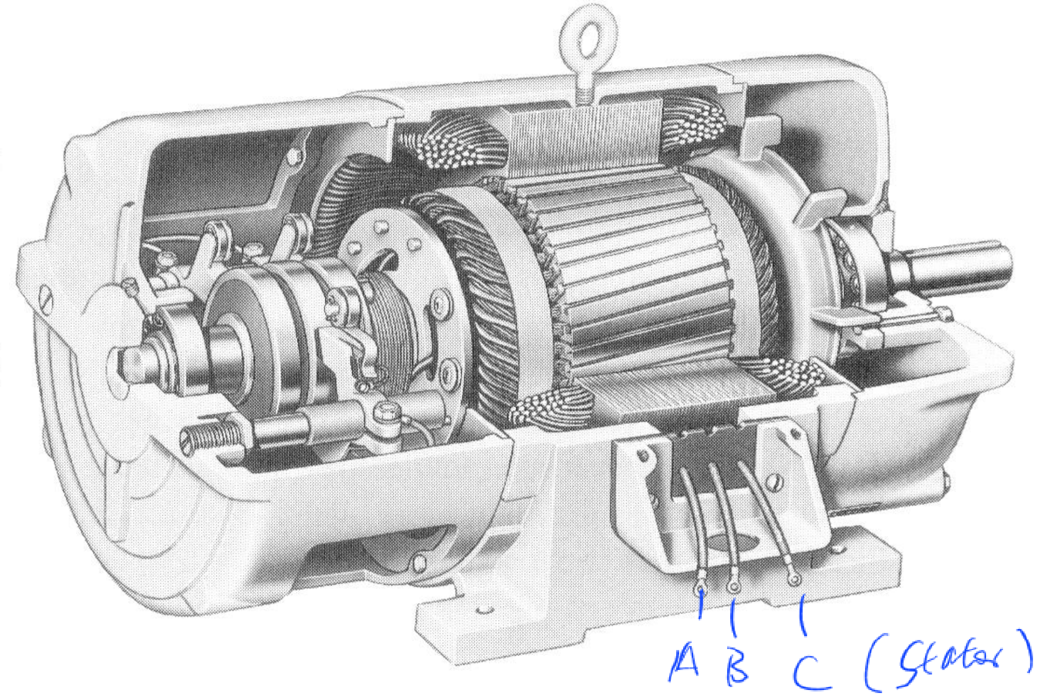
Wound Rotor Winding (Doubly-Fed Ind. Machine - DFIM)

The rotor winding is connected to slip-rings and can be accessed ⇝ gives us more control



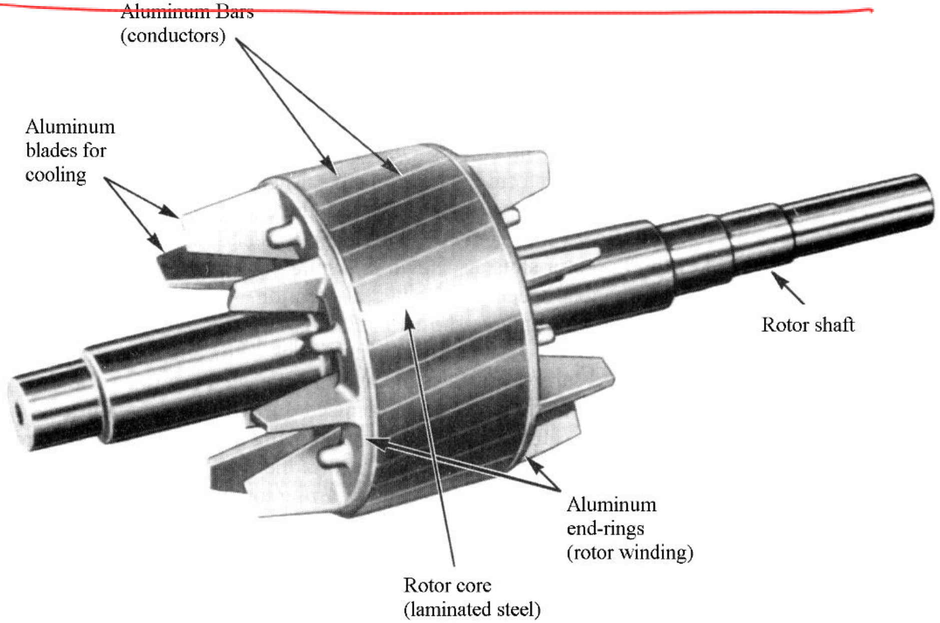


3-φ magnetically coupled

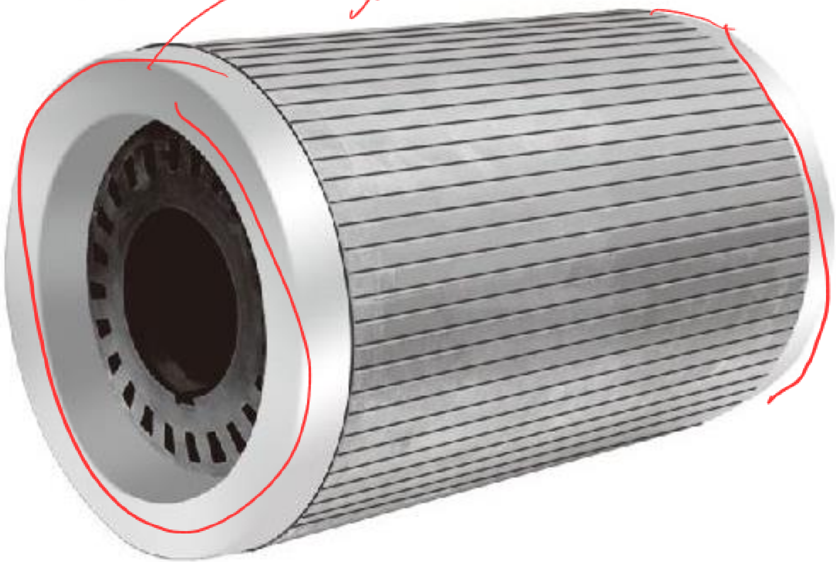


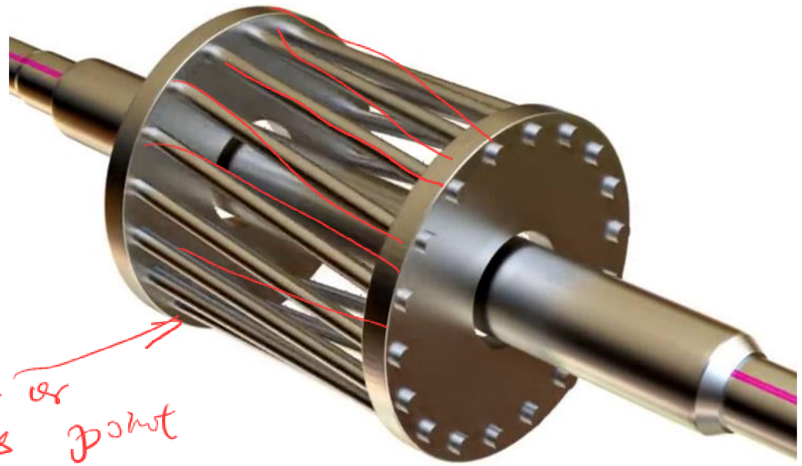
Squirrel-Cage Rotor → No access to rotor

- Rotor skewing is often used to minimize reluctance torque and integration with stator slots/teeth



rings for short circuit



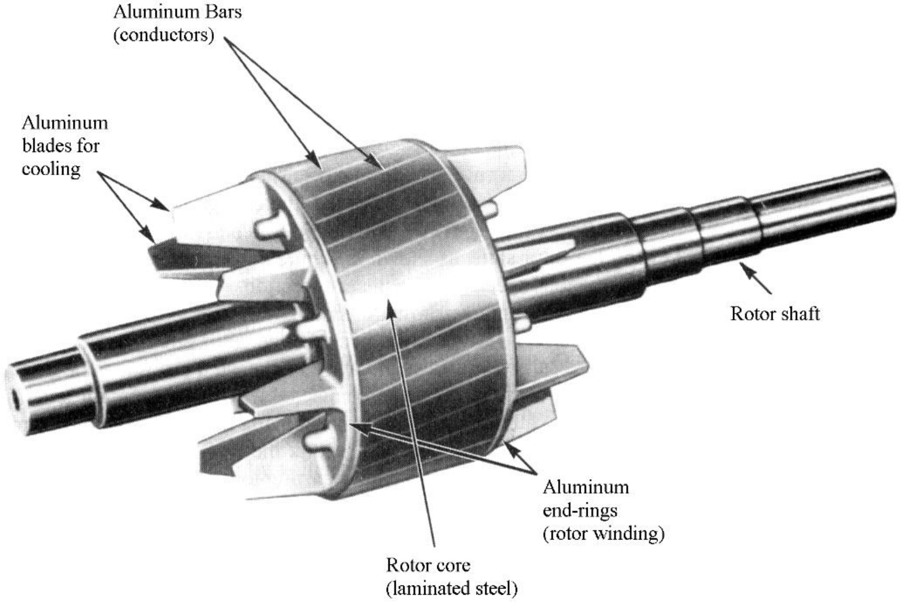


no contact or access point

How many phases would such rotor have? → As many as you want

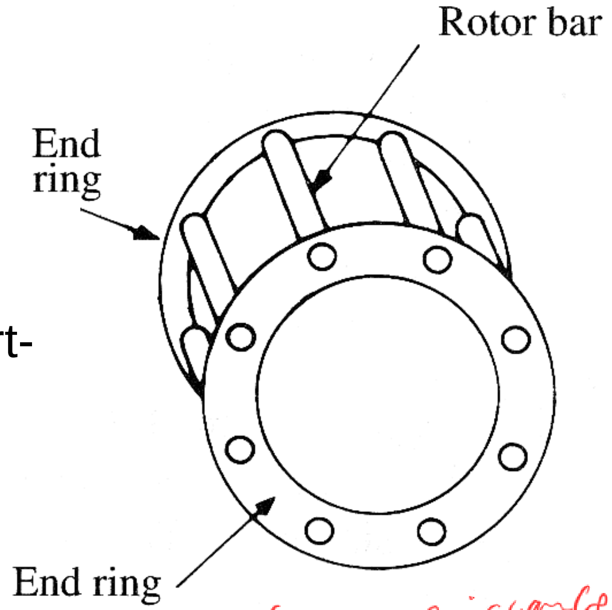
Squirrel-Cage Rotor

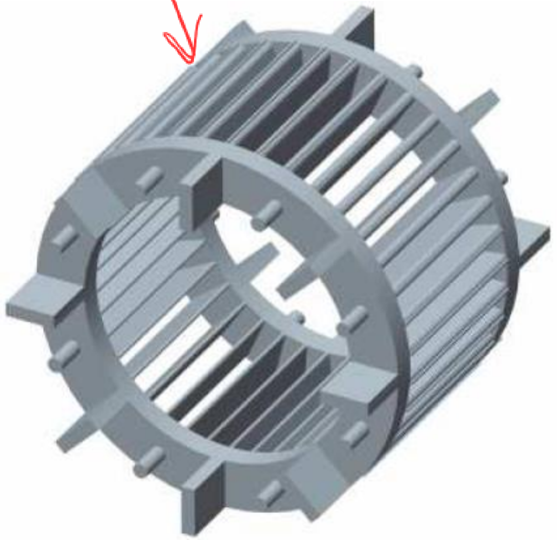
→ Name comes from the cage that squirrel runs



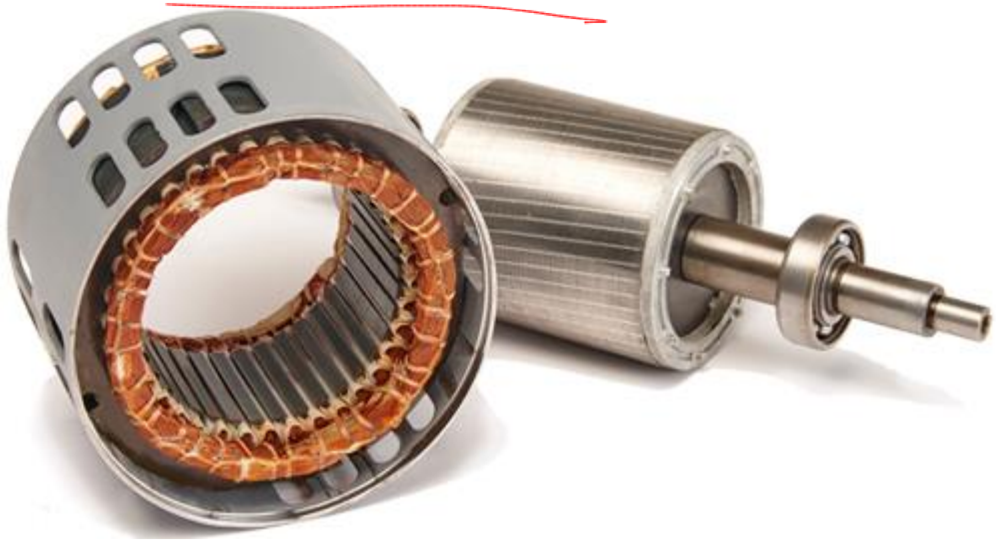
The rotor winding is short-circuited and cannot be accessed!

Squirrel-cage rotor winding

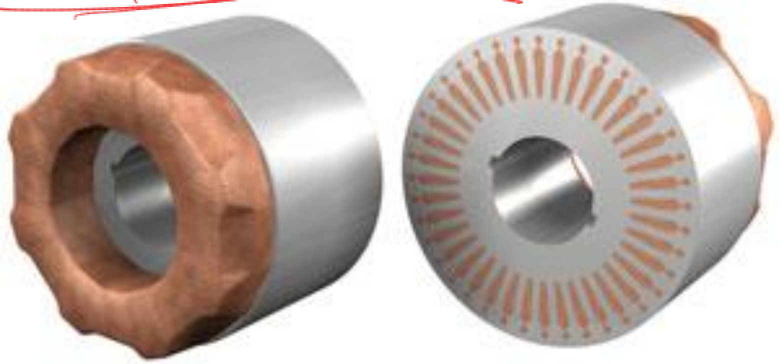




Aluminum



Copper → less resistance → more expensive

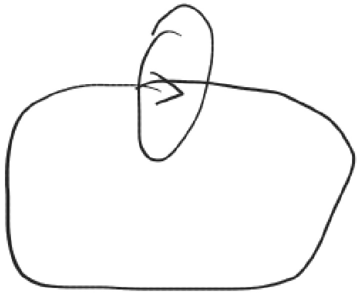


Stator Windings

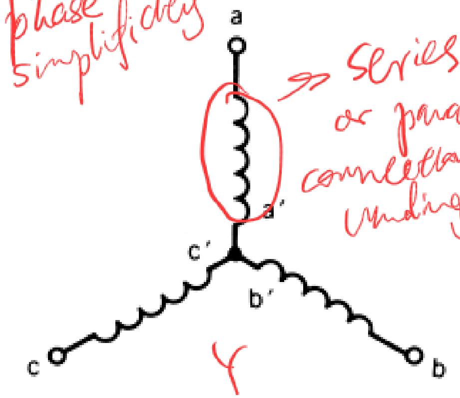
~> # of phases is important for stator. Rotor is to generate torque and act with stator field

- A typical stator would have 3-phases, which may be Y or Δ connected
- Windings may have multiple sections that may form parallel and/or series connection

winding

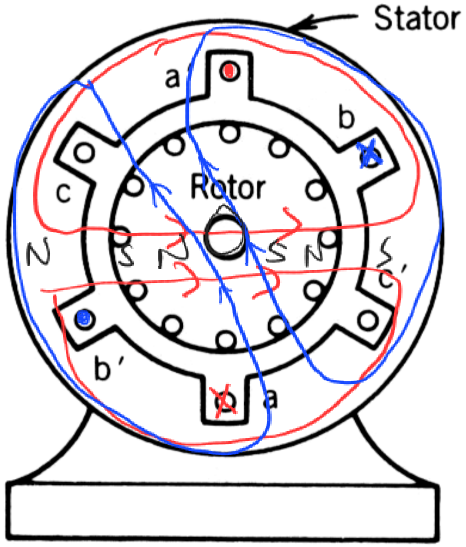


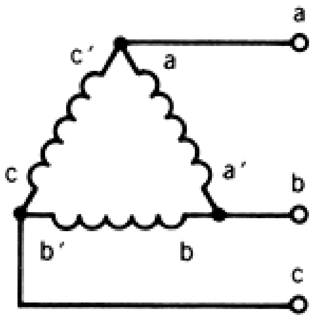
↓ only use 1 windings to represent each phase for simplicity



=> series or parallel connection of windings

Y

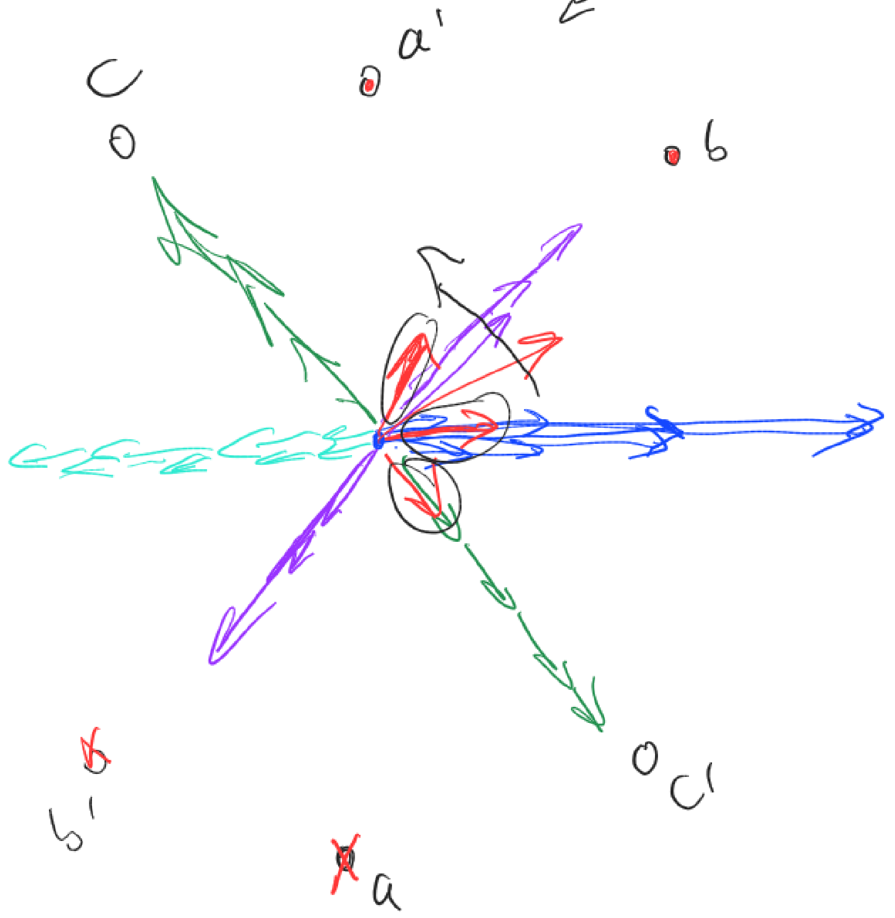


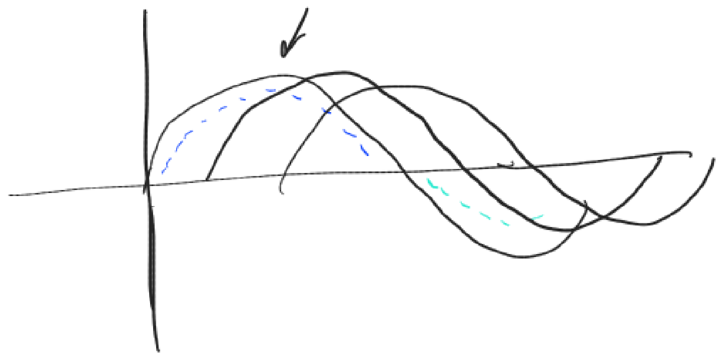


Δ

Rotating Magnetic Field

mechanical placement

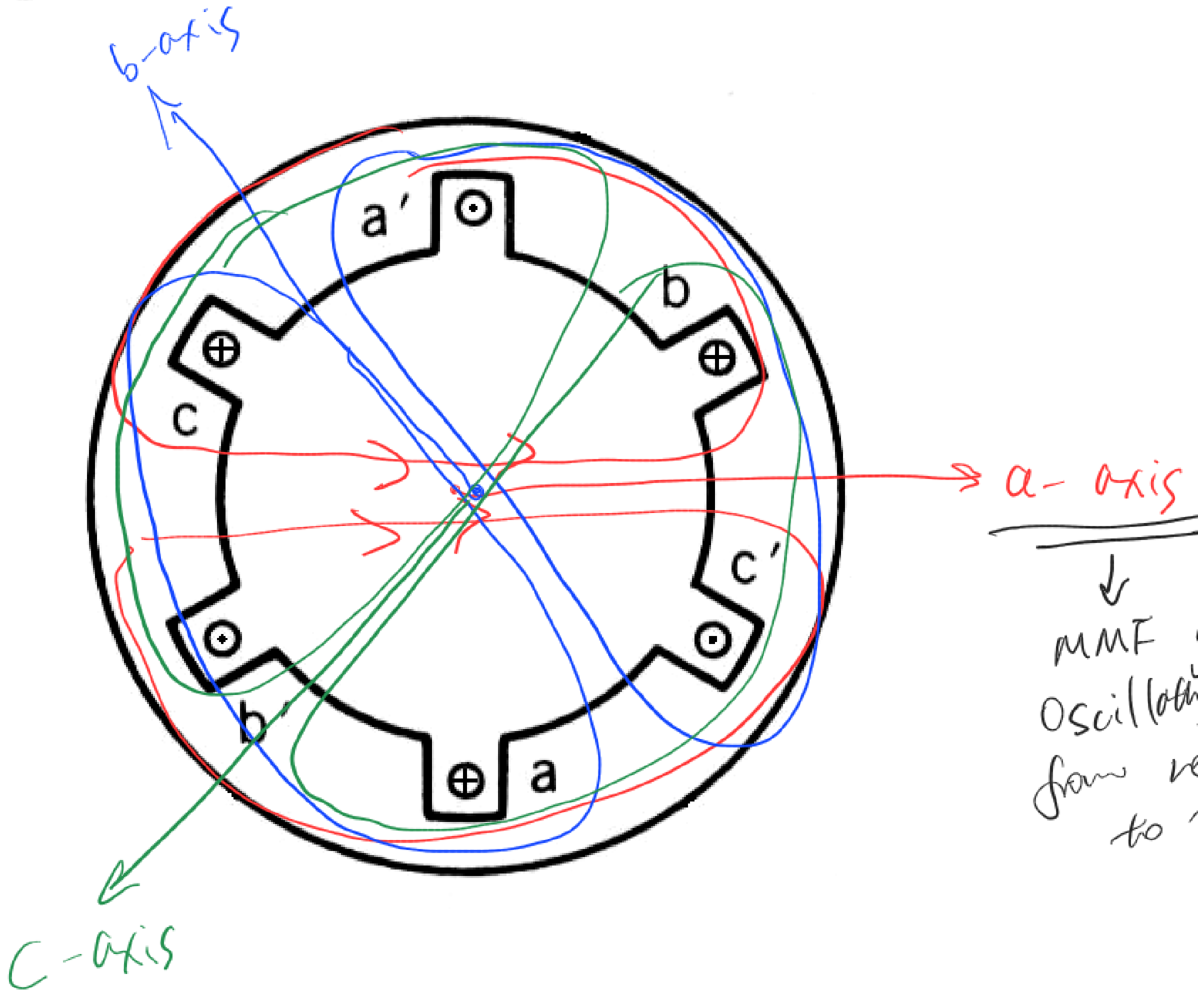




Rotating Magnetic Field

Stator Windings Magnetic Axis

(1) Mechanical displacement of windings
(2) Electrical displacement of current



MMF goes oscillating from negative to positive

magnetic axis
↳ MMF axis

Apply balanced set of currents at f_e = 60Hz or 50Hz

$$\omega_e = 2 \cdot \pi \cdot f_e$$

Current Supplied

$$\begin{cases} i_a = I_m \cos(\omega_e t) \\ i_b = I_m \cos(\omega_e t - 120^\circ) \\ i_c = I_m \cos(\omega_e t + 120^\circ) \end{cases}$$

MMFs in each axis

resulting MMF

$$\begin{cases} F_m = NI_m \\ F_a = F_m \cos(\omega_e t) \\ F_b = F_m \cos(\omega_e t - 120^\circ) \\ F_c = F_m \cos(\omega_e t + 120^\circ) \end{cases}$$

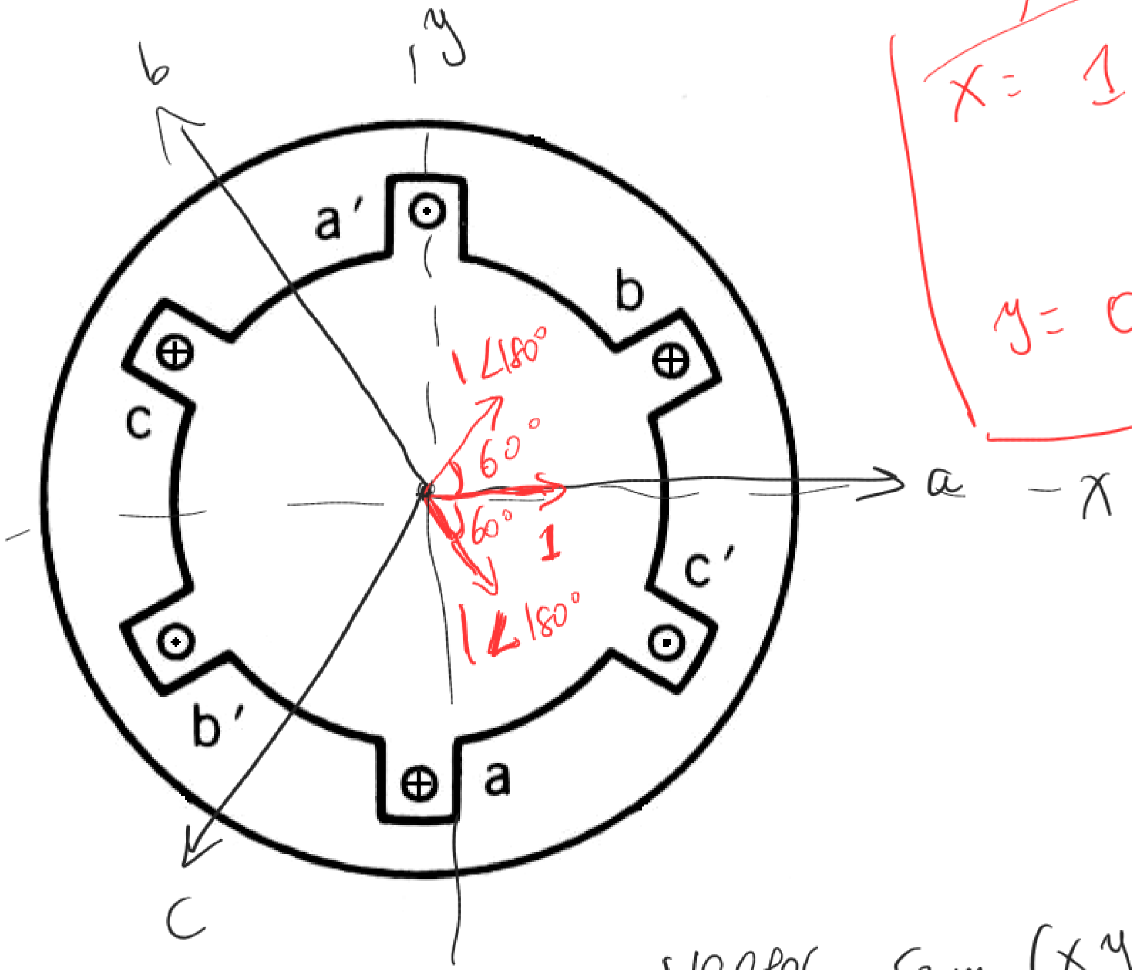
Rotating Magnetic Field

Stator Windings Magnetic Axis

$\vec{F}_{net} = (1+2\cos(60°),\ 0) \rightsquigarrow 1+2\cos(60°) + j0 \Rightarrow e^{j0}$

$x = 1 + 1\cos(60°)$
$\quad + 1\cos(60°)$
$\quad = 1 + 2\cos(60°)$

$y = 0$



Apply balanced set of currents at f_e = 60Hz or 50Hz

$$\omega_e = 2\cdot\pi\cdot f_e$$

$$i_a = I_m \cos(\omega_e t)$$

$$i_b = I_m \cos(\omega_e t - 120^\circ)$$

$$i_c = I_m \cos(\omega_e t + 120^\circ)$$

MMFs in each axis

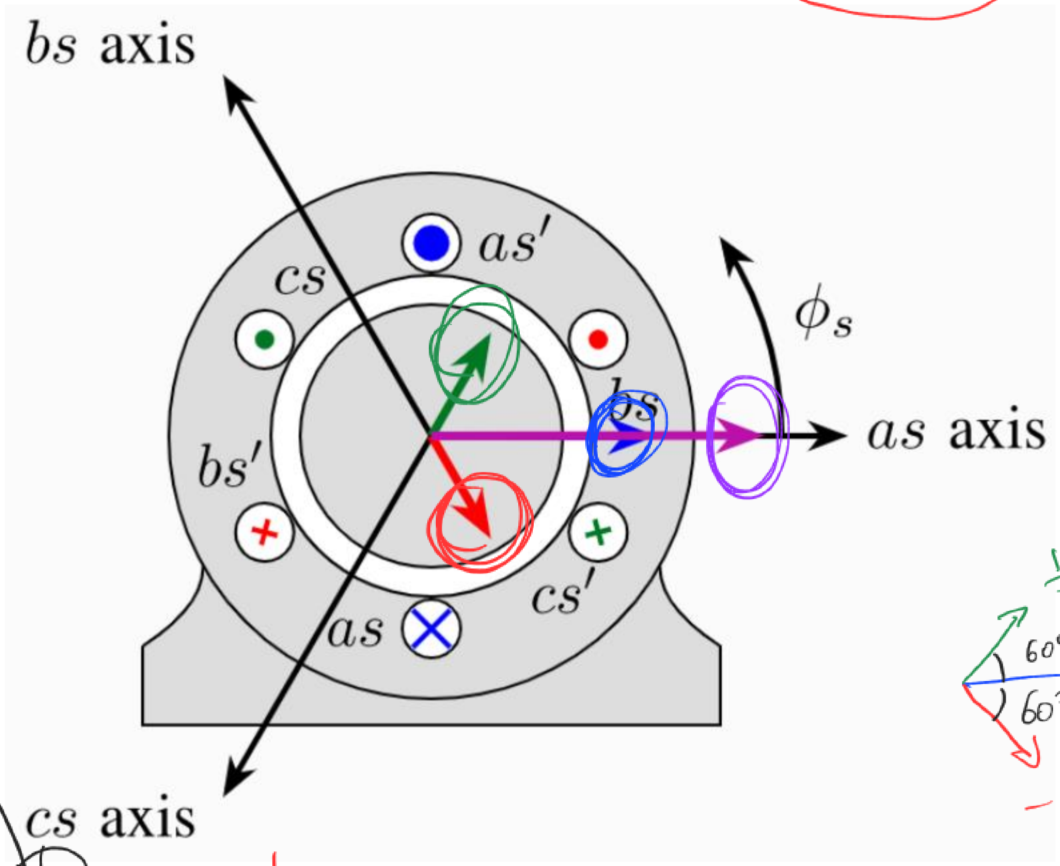
$$F_m = NI_m$$

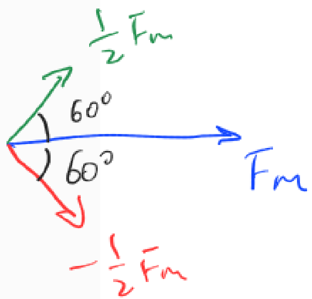
$$\begin{cases} F_a = F_m \cos(\omega_e t) \\ F_b = F_m \cos(\omega_e t - 120^\circ) \\ F_c = F_m \cos(\omega_e t + 120^\circ) \end{cases}$$

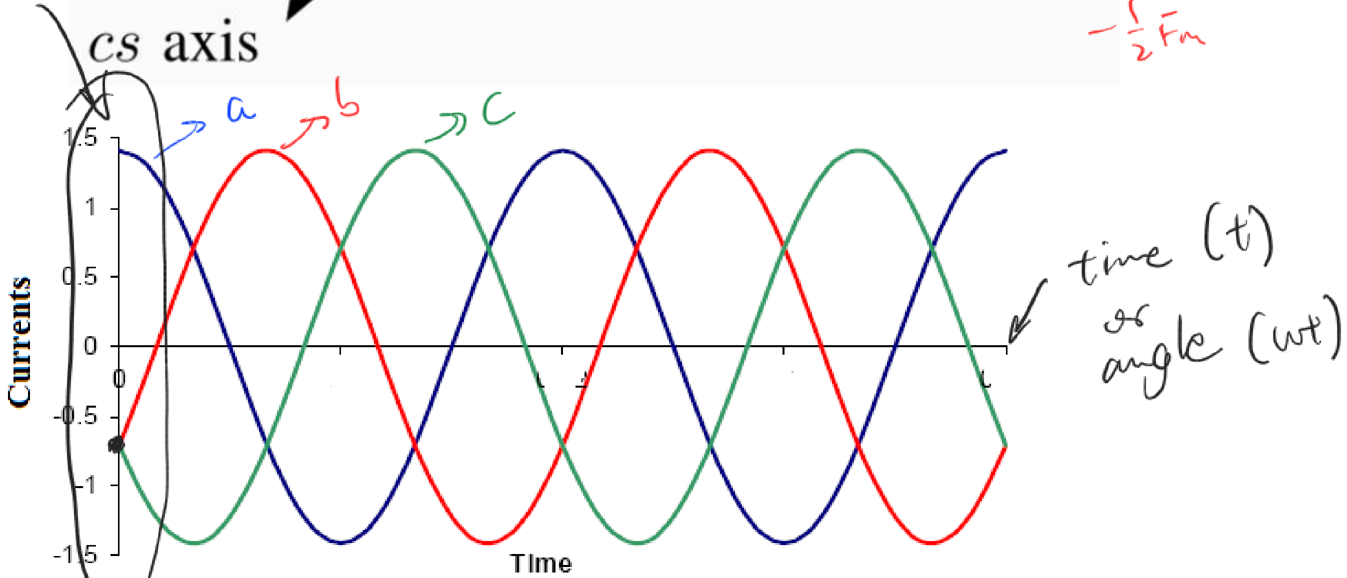
vector sum (x y axis)

Resulting mmf $\mathbf{F}_{net} = \mathbf{F}_a + \mathbf{F}_b + \mathbf{F}_c$

Rotating Magnetic Field at $\omega_e t = 0$







Apply balanced set of currents

$$\begin{cases} i_{as} = I_m \cos(\omega_e t) \\ i_{bs} = I_m \cos(\omega_e t - 120°) \\ i_{cs} = I_m \cos(\omega_e t + 120°) \end{cases}$$

$$\begin{cases} F_{as} = NI_m = F_m \\ F_{bs} = -\frac{1}{2} NI_m = -\frac{1}{2} F_m \\ F_{cs} = -\frac{1}{2} F_m \end{cases}$$

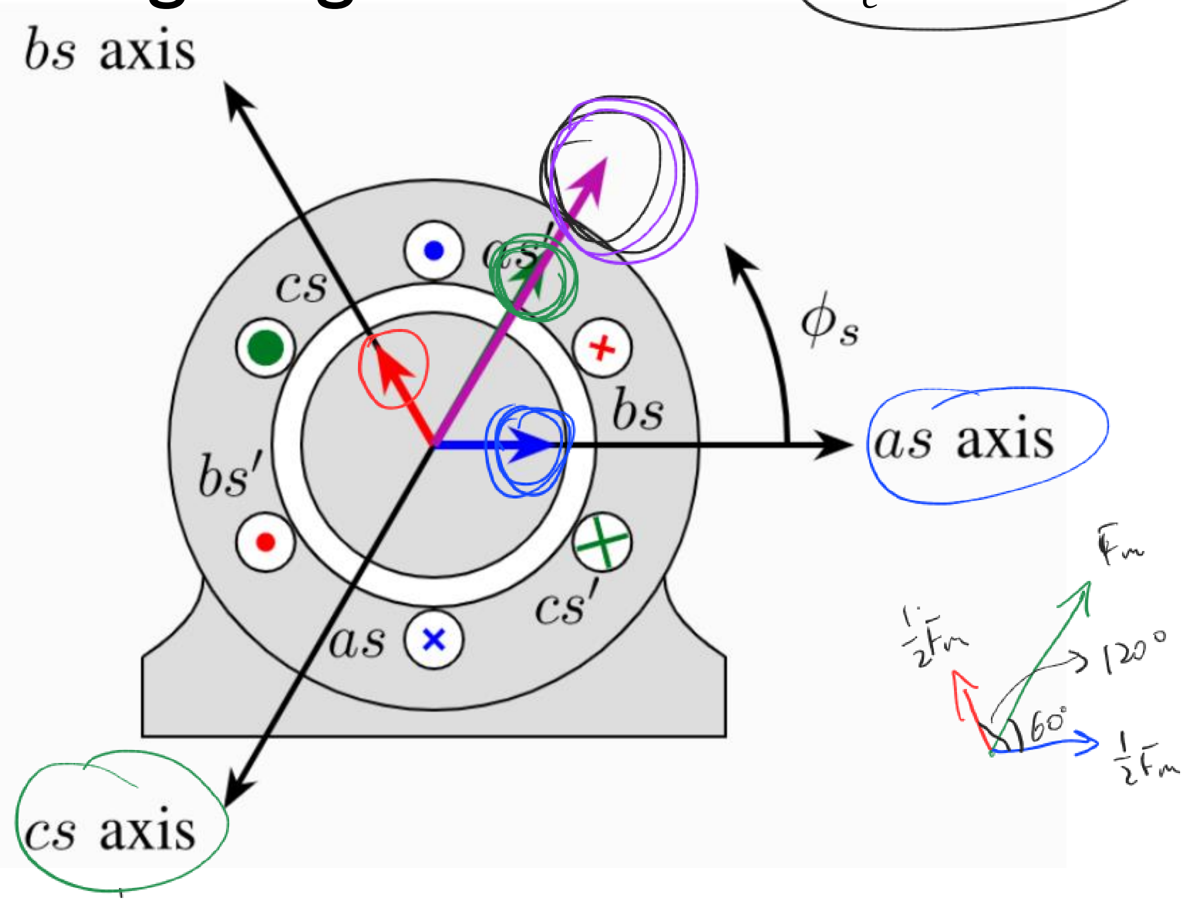
Resulting MMF

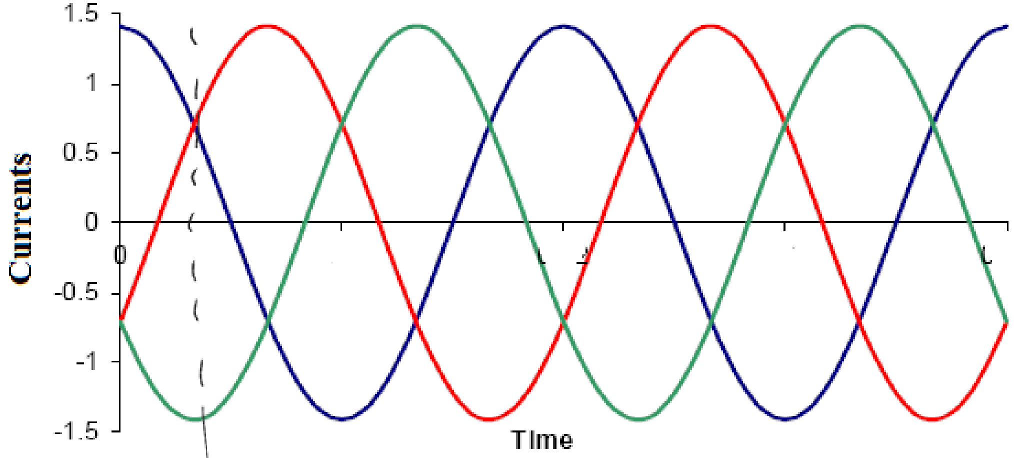
$$\mathbf{F}_s = \mathbf{F}_{as} + \mathbf{F}_{bs} + \mathbf{F}_{cs}$$

$$= F_m + 2 \times \frac{1}{2} F_m \cos(60°)$$

$$= \left(\frac{3}{2} F_m \angle 0°\right)$$

Rotating Magnetic Field at $\omega_e t = 60^\circ$





Apply balanced set of currents

$$\begin{cases} i_{as} = I_m \cos(\omega_e t) \\ i_{bs} = I_m \cos(\omega_e t - 120^\circ) \\ i_{cs} = I_m \cos(\omega_e t + 120^\circ) \end{cases}$$

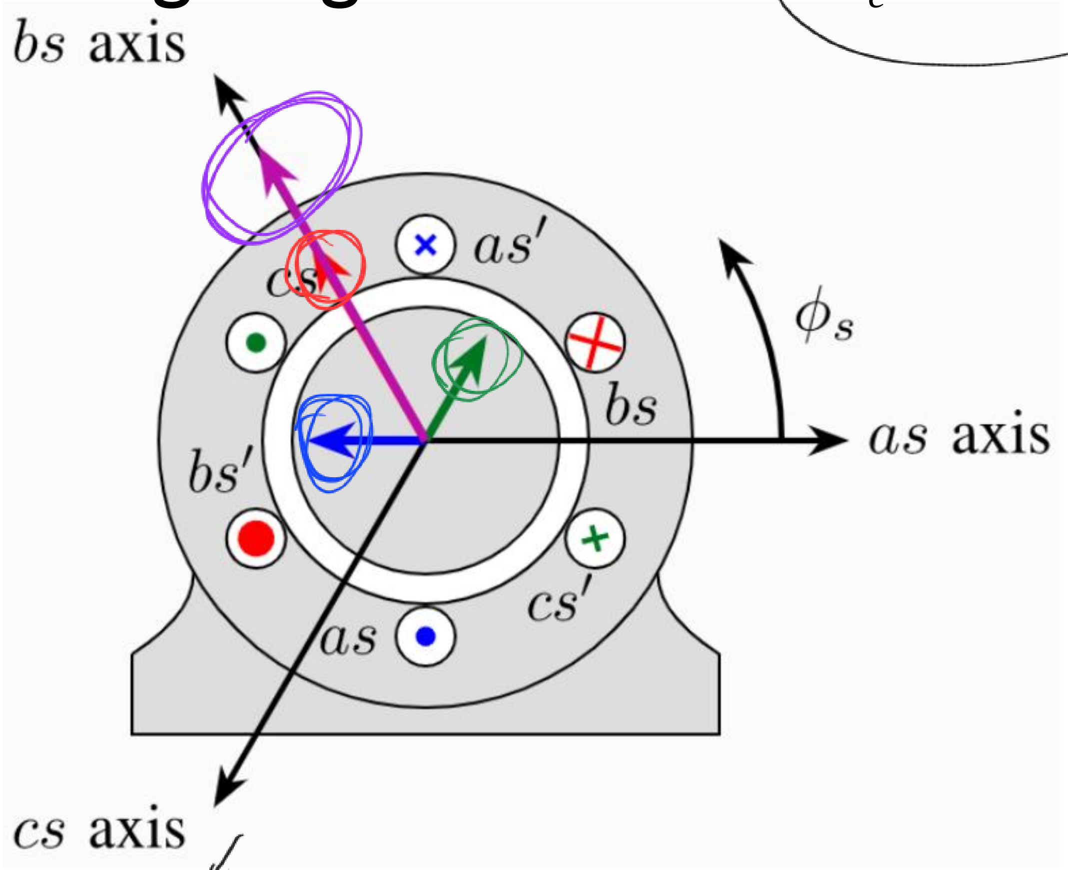
$$\begin{cases} F_{as} = +\frac{1}{2} F_m \\ F_{bs} = +\frac{1}{2} F_m \\ F_{cs} = -F_m \end{cases}$$

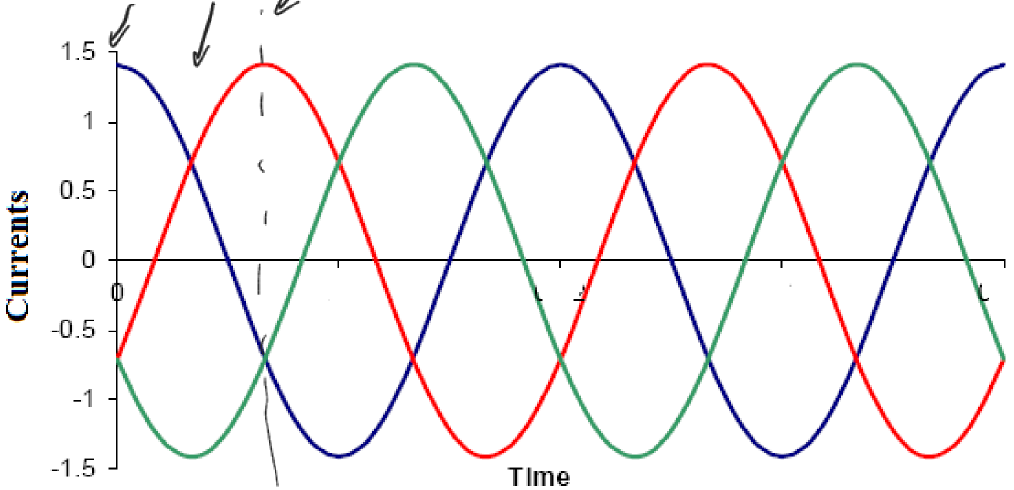
Resulting MMF

$$\mathbf{F}_s = \mathbf{F}_{as} + \mathbf{F}_{bs} + \mathbf{F}_{cs}$$

$$= \frac{3}{2} F_m \angle 60^\circ$$

Rotating Magnetic Field at $\omega_e t = 120^\circ$





Apply balanced set of currents

$$\begin{cases} i_{as} = I_m \cos(\omega_e t) \\ i_{bs} = I_m \cos(\omega_e t - 120^\circ) \\ i_{cs} = I_m \cos(\omega_e t + 120^\circ) \end{cases}$$

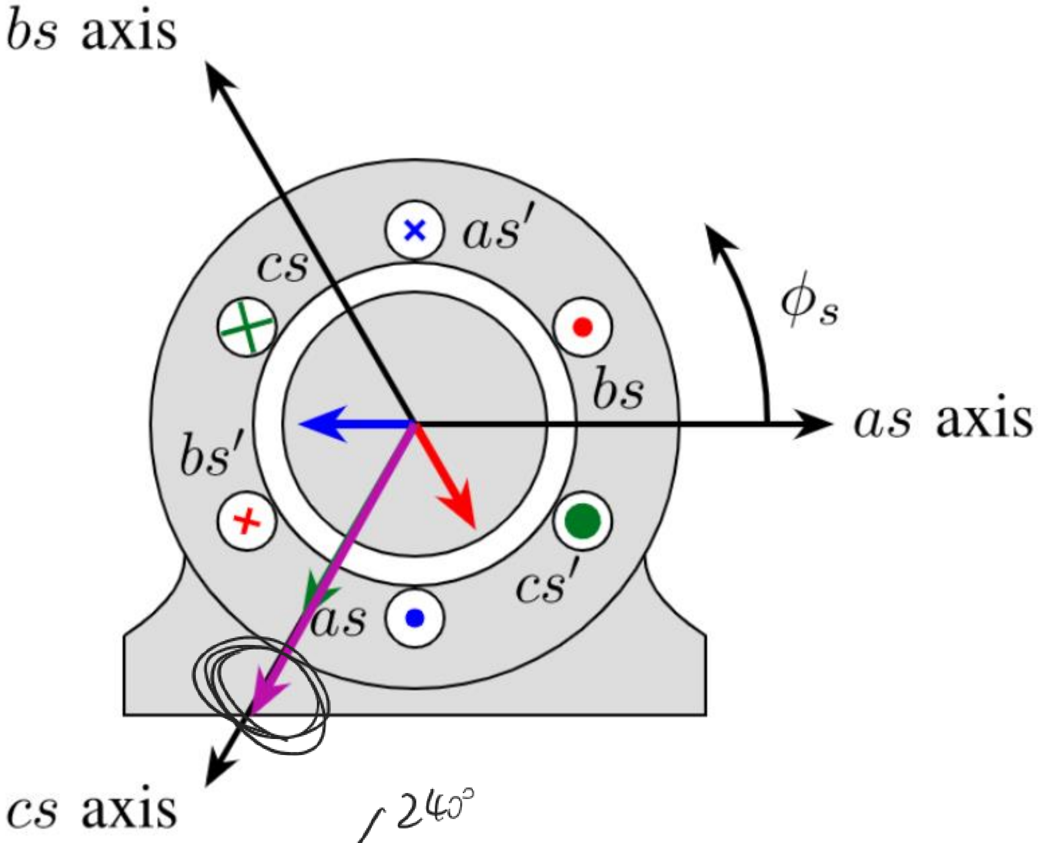
$$\begin{cases} F_{as} = -\frac{1}{2} F_m \\ F_{bs} = + F_m \\ F_{cs} = -\frac{1}{2} F_m \end{cases}$$

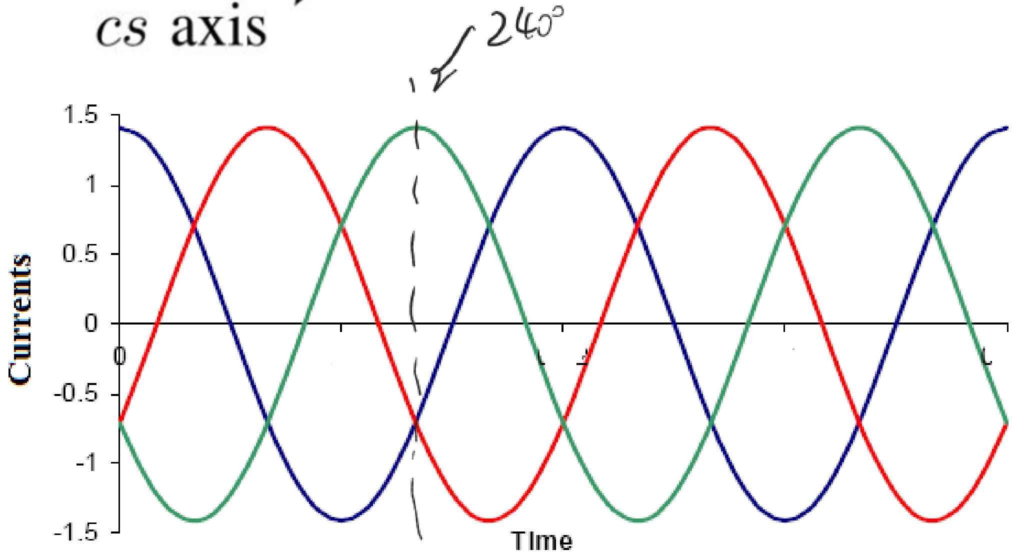
Resulting MMF

$$\mathbf{F}_s = \mathbf{F}_{as} + \mathbf{F}_{bs} + \mathbf{F}_{cs}$$

$$= \frac{3}{2} F_m \angle 120^\circ$$

Rotating Magnetic Field at $\omega_e t = 240^\circ$





Apply balanced set of currents

$$\begin{cases} i_{as} = I_m \cos(\omega_e t) \\ i_{bs} = I_m \cos(\omega_e t - 120^\circ) \\ i_{cs} = I_m \cos(\omega_e t + 120^\circ) \end{cases}$$

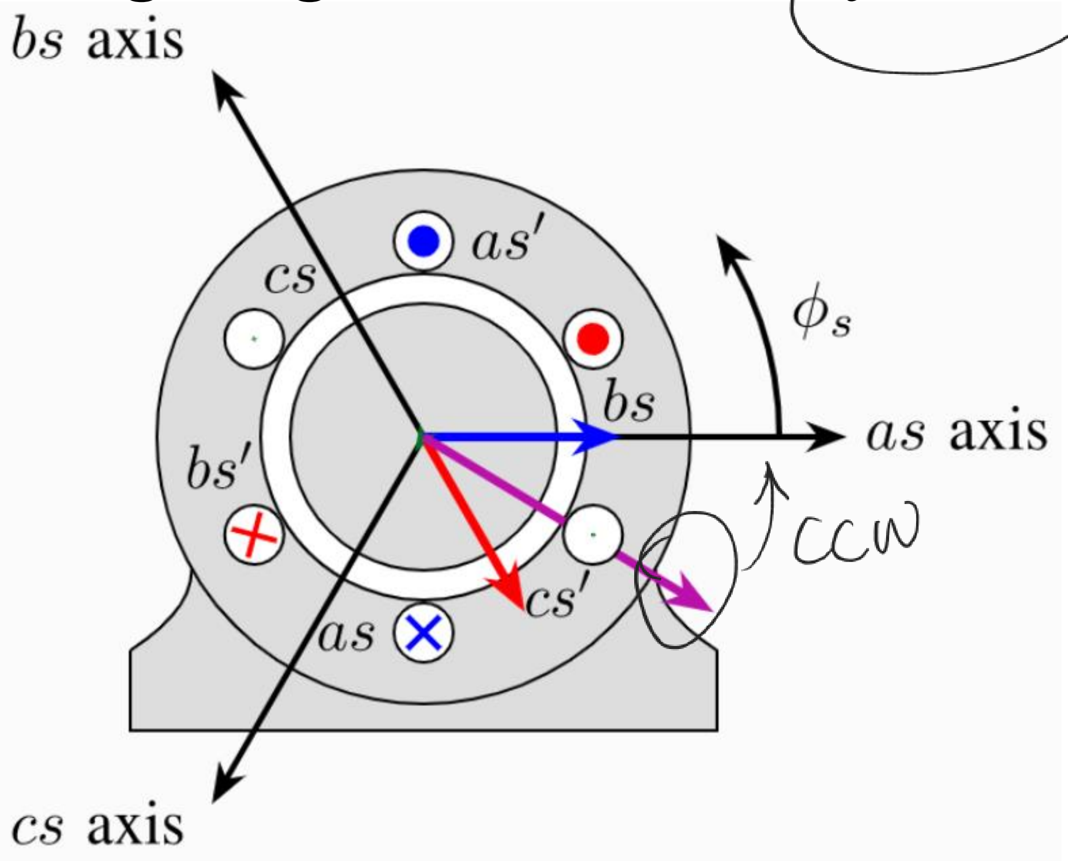
$$\begin{cases} F_{as} = -\frac{1}{2} F_m \\ F_{bs} = -\frac{1}{2} F_m \\ F_{cs} = \cancel{+} F_m \end{cases}$$

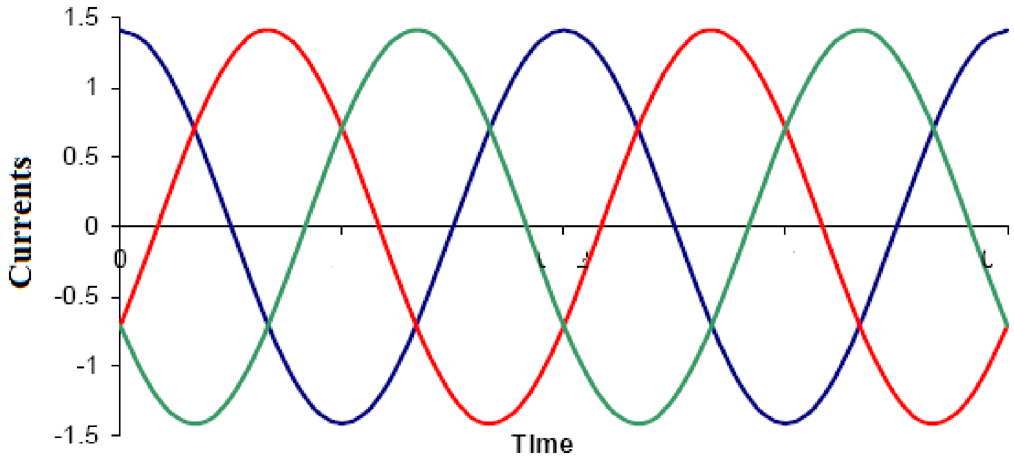
Resulting MMF

$$\mathbf{F}_s = \mathbf{F}_{as} + \mathbf{F}_{bs} + \mathbf{F}_{cs}$$

$$= \frac{3}{2} F_m \angle 240^\circ$$

Rotating Magnetic Field at $\omega_e t = 330^\circ$





Apply balanced set of currents

$$
\begin{cases}
i_{as} = I_m \cos(\omega_e t) \\
i_{bs} = I_m \cos(\omega_e t - 120^\circ) \\
i_{cs} = I_m \cos(\omega_e t + 120^\circ)
\end{cases}
$$

$$
\begin{cases}
F_{as} = \\
F_{bs} = \\
F_{cs} =
\end{cases}
$$

Resulting MMF

$$\mathbf{F}_s = \mathbf{F}_{as} + \mathbf{F}_{bs} + \mathbf{F}_{cs}$$

$$= \frac{3}{2} F_m \angle 330^\circ$$

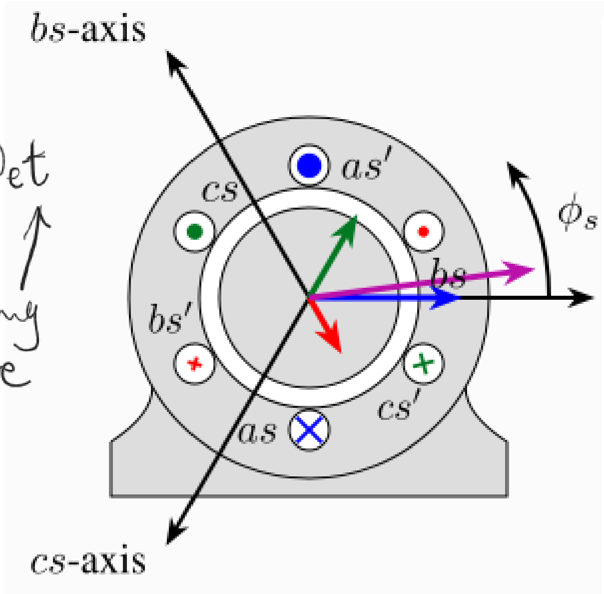
Rotating Magnetic Field

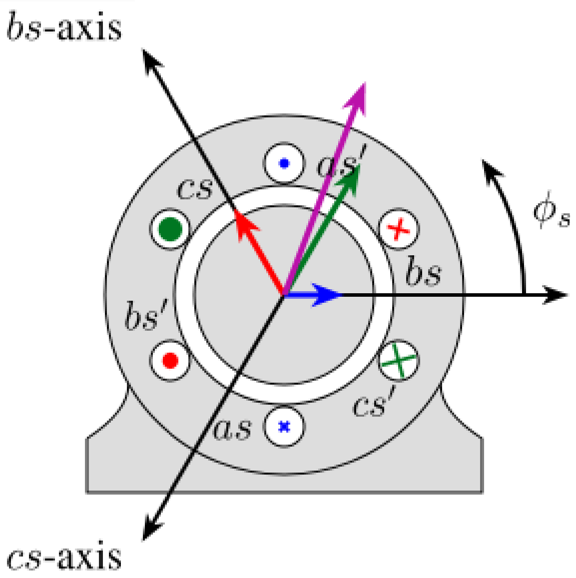
→ CCW

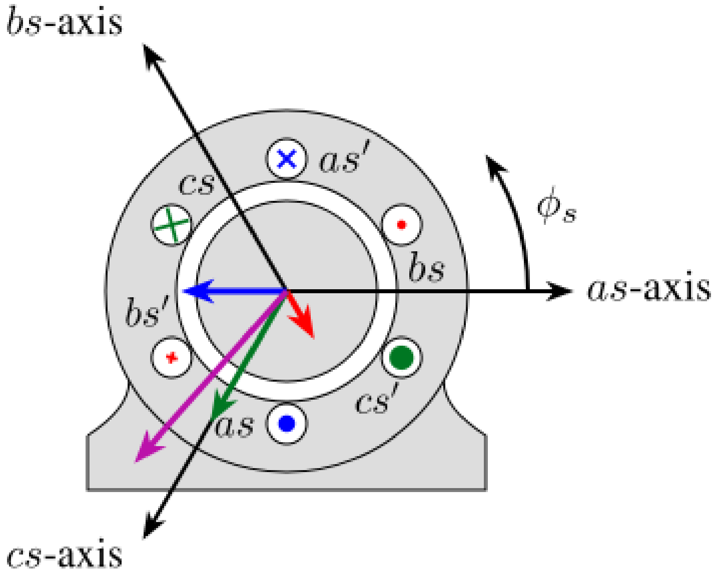
→ Constant amplitude of $\frac{3}{2} N I_m$

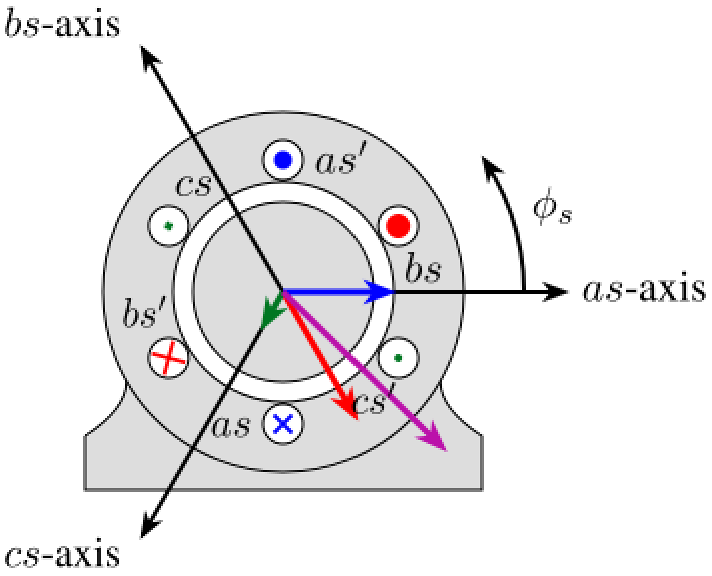
$\vec{F}_{net} = \frac{3}{2} F_m \angle \omega_e t$

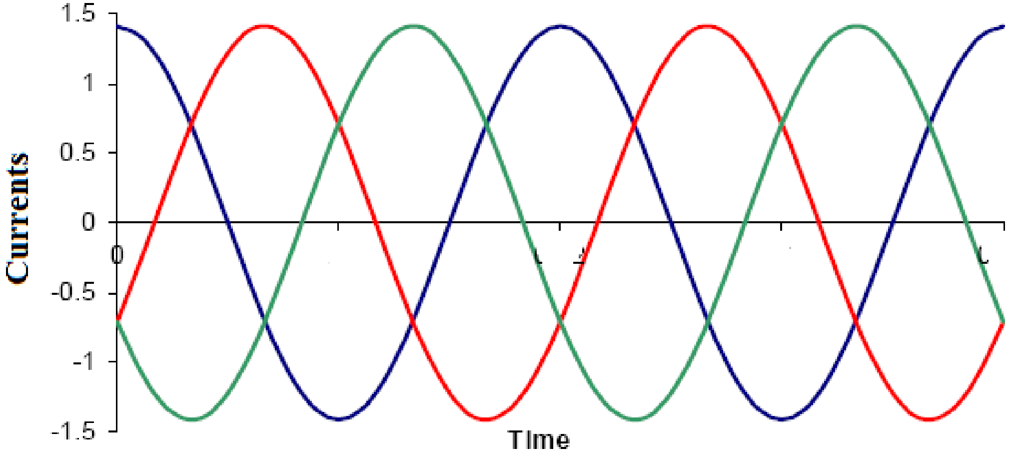
rotating angle











Producing Rotating Magnetic Field

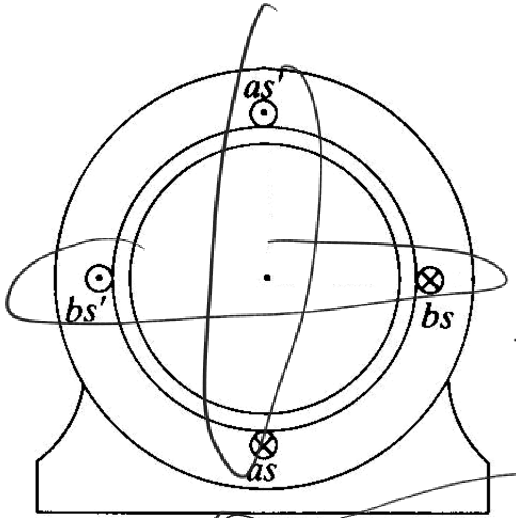
1. Given a set of AC currents shifted in time → electrical
2. Apply these currents to shifted in space stator windings → Produce MMF vector $\mathbf{F}_s$ that: → mechanical
   - Has constant magnitude
   - Rotates in space

2-ϕ

$$i_a = I_m \cos(\omega_e t)$$
$$i_b = I_m \cos(\omega_e t - 90^\circ)$$

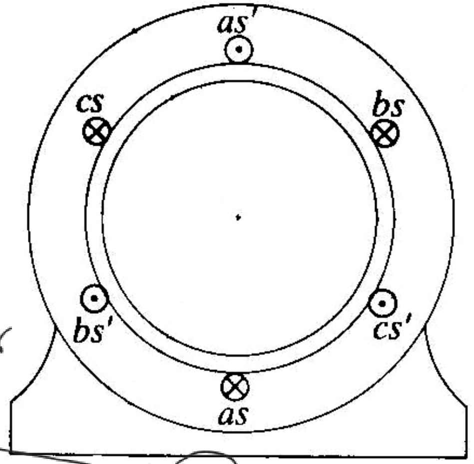
3-ϕ

$$i_a = I_m \cos(\omega_e t)$$
$$i_b = I_m \cos(\omega_e t - 120^\circ)$$
$$i_c = I_m \cos(\omega_e t + 120^\circ)$$



$$\mathbf{F}_s = \left(\frac{2}{2}\right) F_m \angle \theta_e$$ $= \omega t$

Increase # of phases: you get a larger net MMF given the same current amplitude



$$\mathbf{F}_s = \left(\frac{3}{2}\right) F_m \angle \theta_e$$

How many phases can you have ?

↳ min of 2 phases

↳ as many as you want

↳ Typically multiple of 3

How do you change direction of rotation ?

↳ a – b – c → CCW

a – c – b → CW

↳ change any 2 sequence

Looking ahead…

- Continue **Module 5**