ELEC 342
Electromechanical Energy Conversion and Transmission

2025-26 Winter Term 2

Lecture 23

April 7, 2026

Zhi Jin (Justin) Zhang

Course Logistics

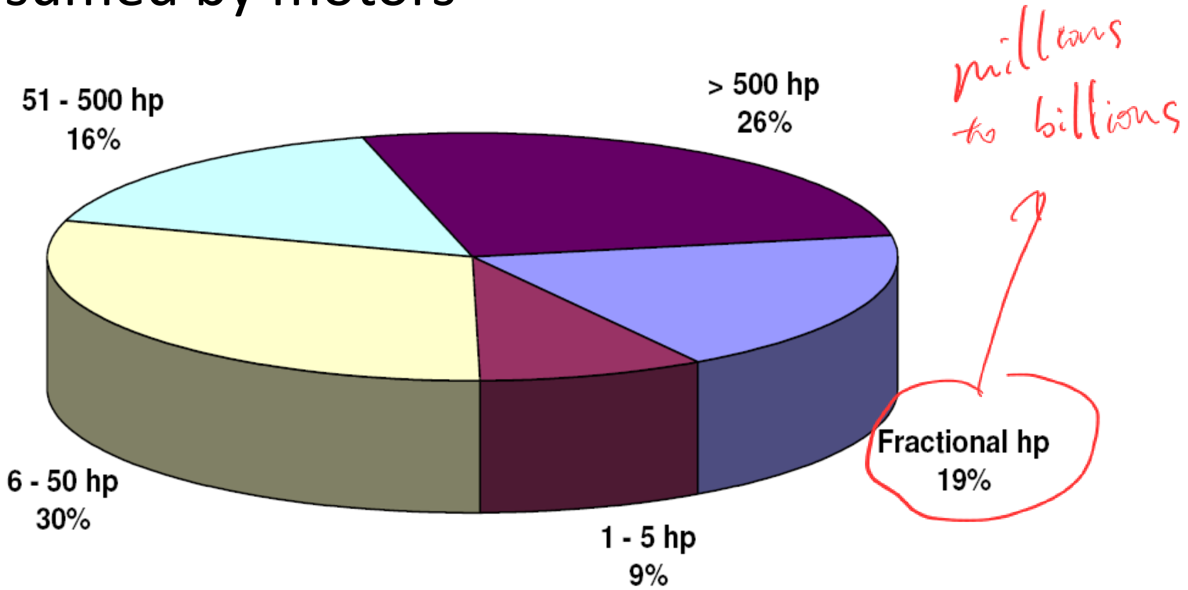
- Lab 5 Monday section moved to Wednesday (Apr. 8) at 10:30 AM
  - Only Monday section is modified, Friday sections are not impacted
- No tutorial this Friday
- Office hour
  - My regular office hour on April 8 and 15 at 4 PM
  - The TA will hold an additional office hour on either April 13, 14, 16, or 17: **vote on Piazza**
- SEI survey: March 28 – April 13
- Final exam: Apr. 19 @ 12 PM in IRC 4

Module 7: Small Motors (overview only, will not be tested)

Objectives & important concepts

- PM Brushless DC Machines (Ch. 6.13)
- Reluctance Motors (Ch. 6.14)
- Single Phase AC Motors (Ch. 7.1 & 7.2)

- Electrical Energy Utilization
  - In BC, about 65% of all electricity is consumed by motors
  - For industry it is about 85%



PM Synchronous Brushless DC (BLDC) Machines (Ch. 6.13)

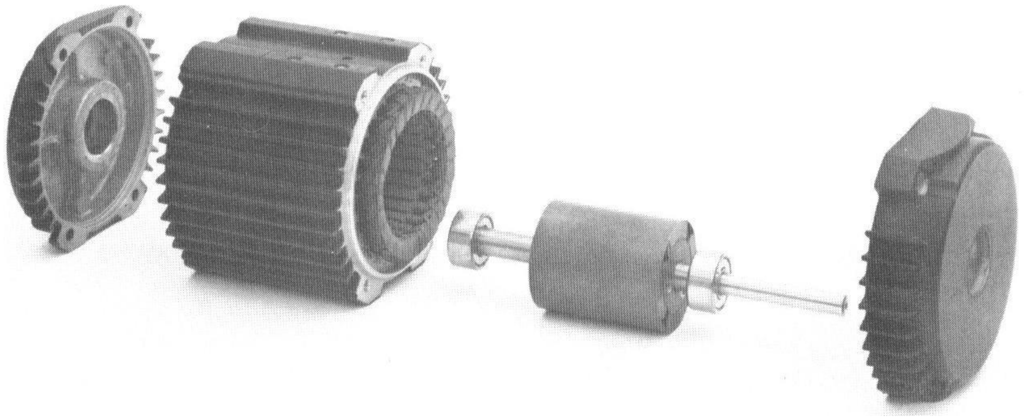
Objectives:

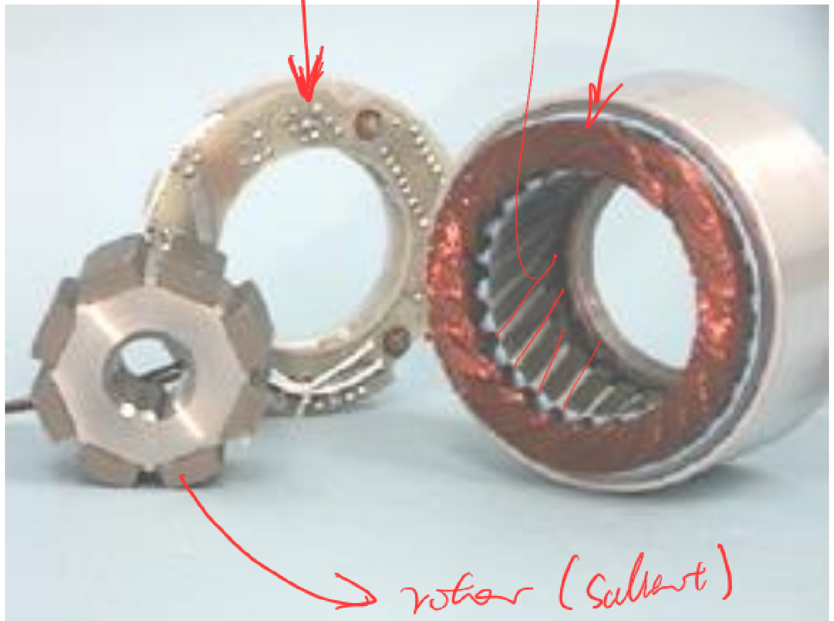
- Provide overview, understand concepts and principles
- Types and construction of commonly used Brushless DC and Servo Motors
- Applications of BLDC motors
- Principle of operation & torque production
- Similarity with conventional brushed DC Motors
- Principle of PWM drive of Brushless DC Motors

Skew to smooth the air gap

Converter

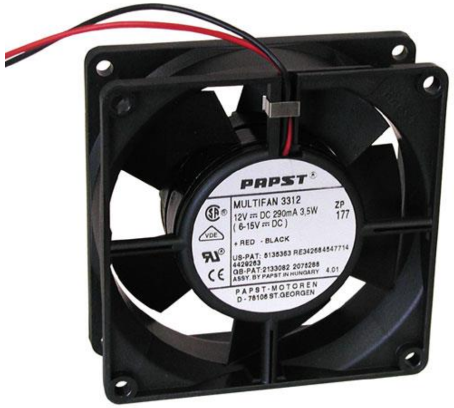
Stator





Applications of Typical Brushless DC Motors

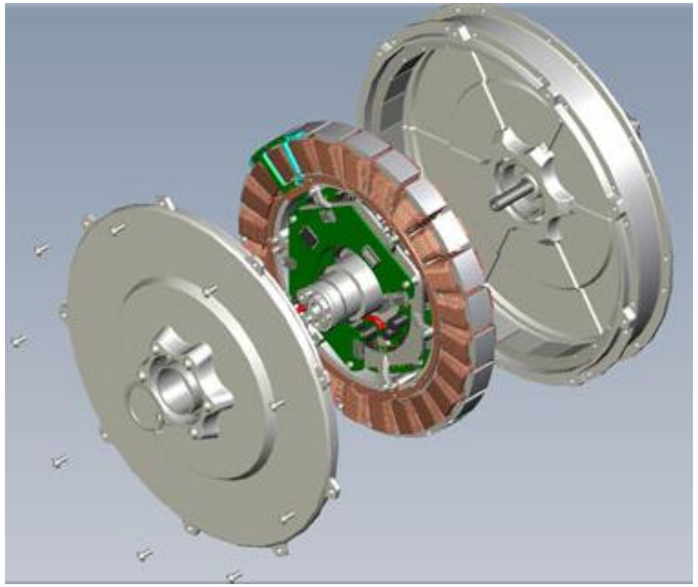
Computers



toys

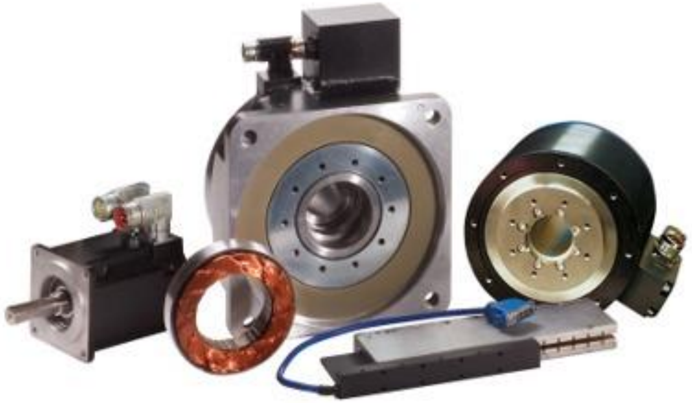
Propulsion & Transportation

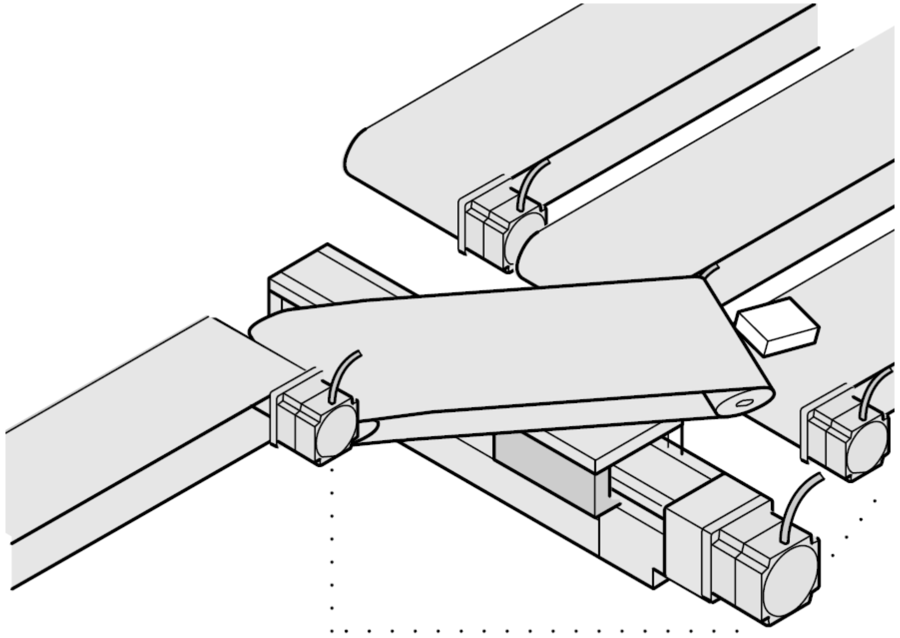
In-Wheel motors

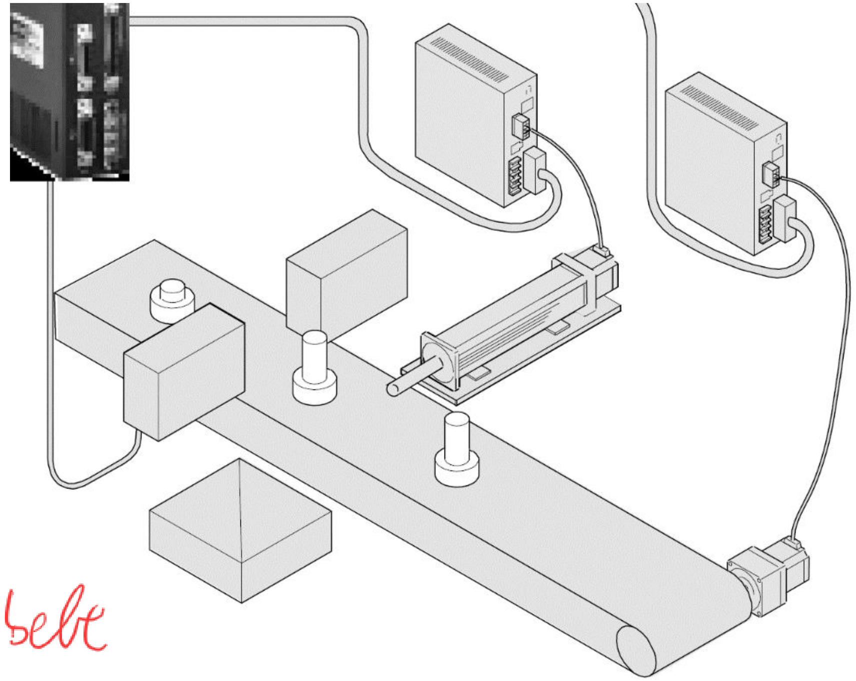


Applications of Typical Brushless DC Motors

Servo motors for positioning and industrial automation



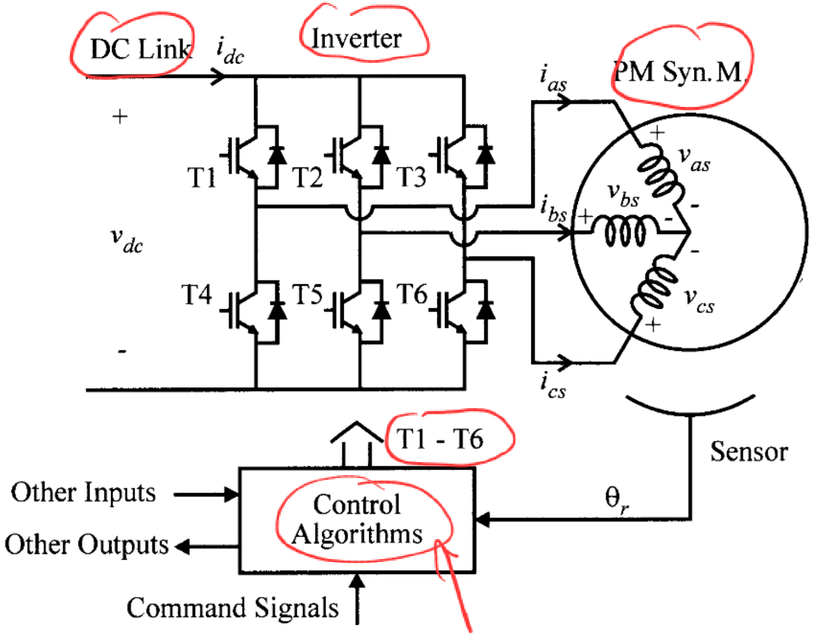




Conveyor belt

Typical Configurations of BLDC Motors

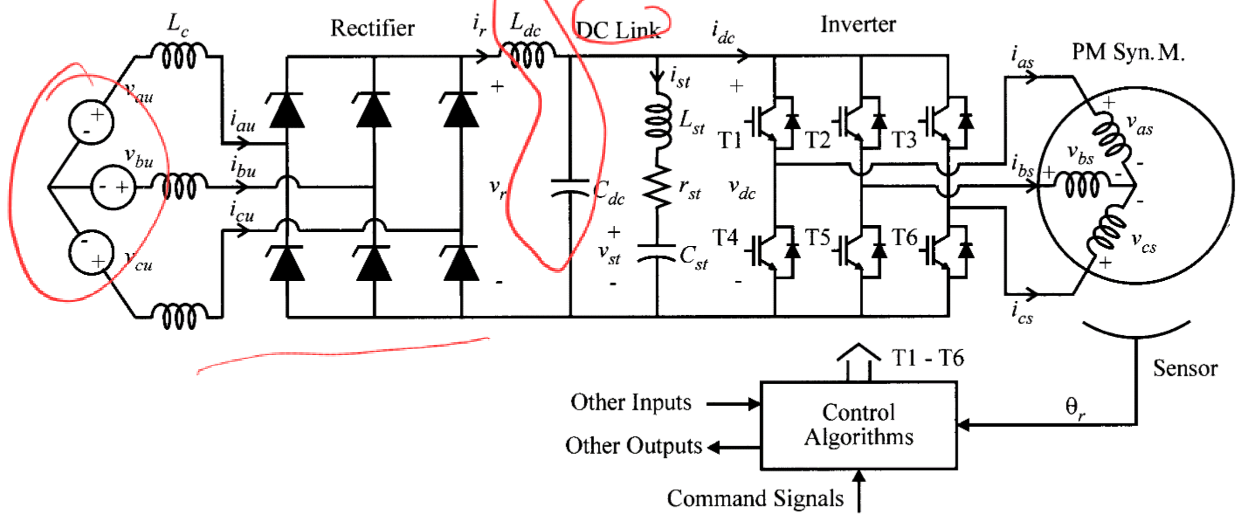
DC input:
requires additional DC power supply (24 – 48V DC)



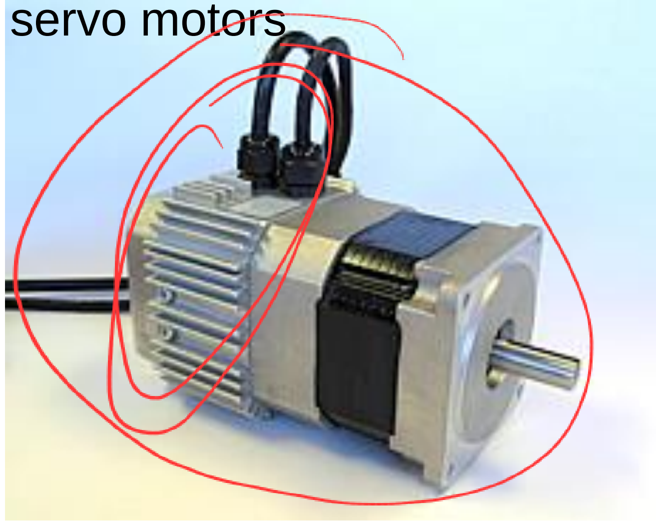
BLDC Motor & Drivers

separate

3-Phase AC input:
no additional power supply is needed (208/120 V AC)



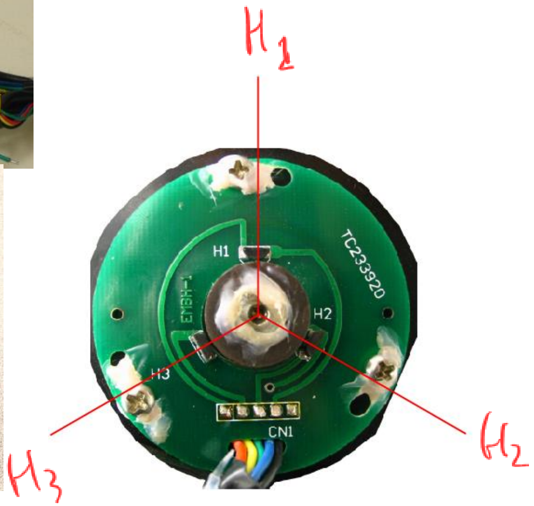
Brushless AC or DC servo motors



Hall-Sensor-Driven BLDC Machine

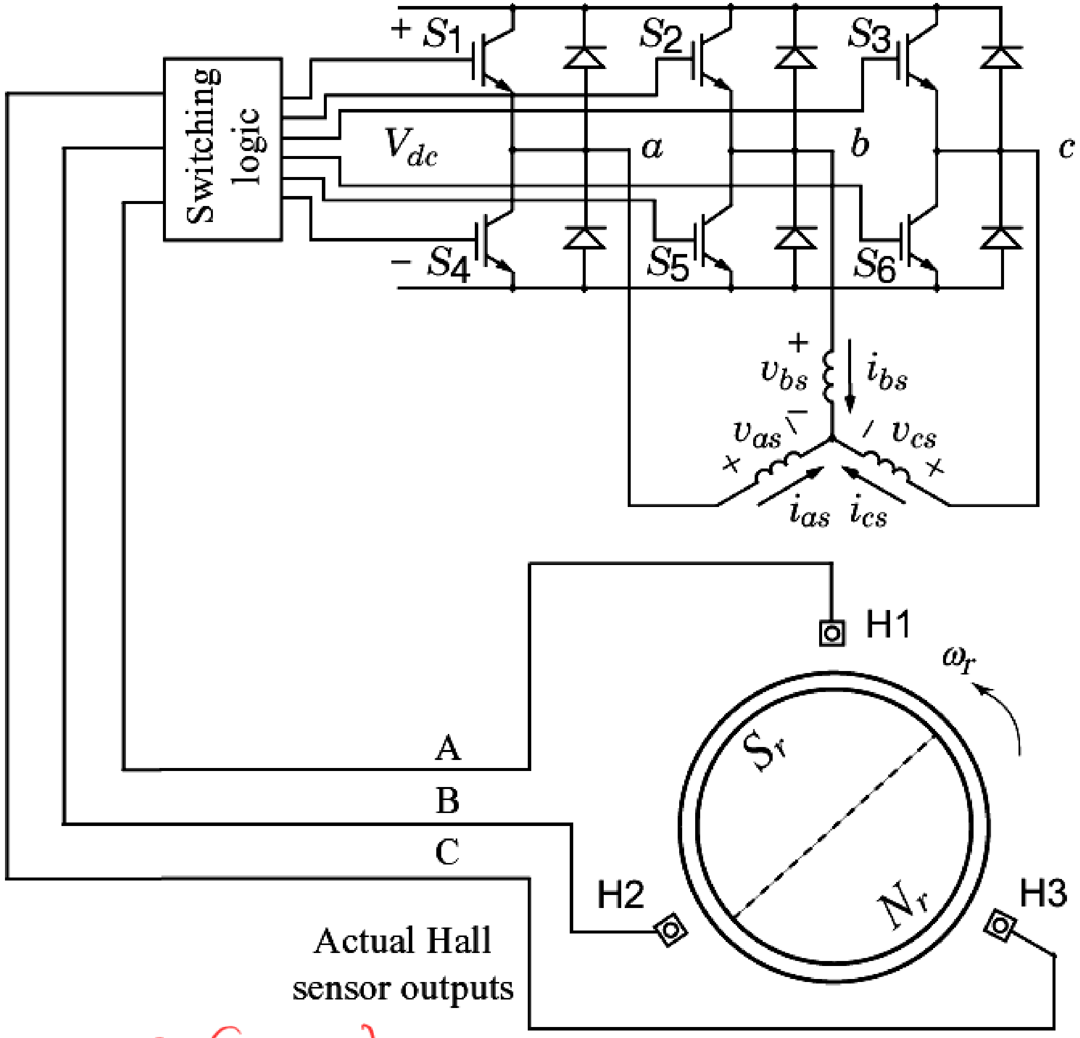
Features

- Simple & low cost
- Work with various loads
- Drivers work with different motors
- Motors work with different drivers
- Good speed/torque characteristics
- High dynamic response
- High efficiency
- Wide speed ranges



$H_1, H_2, H_3 \in \{0, 1\}$

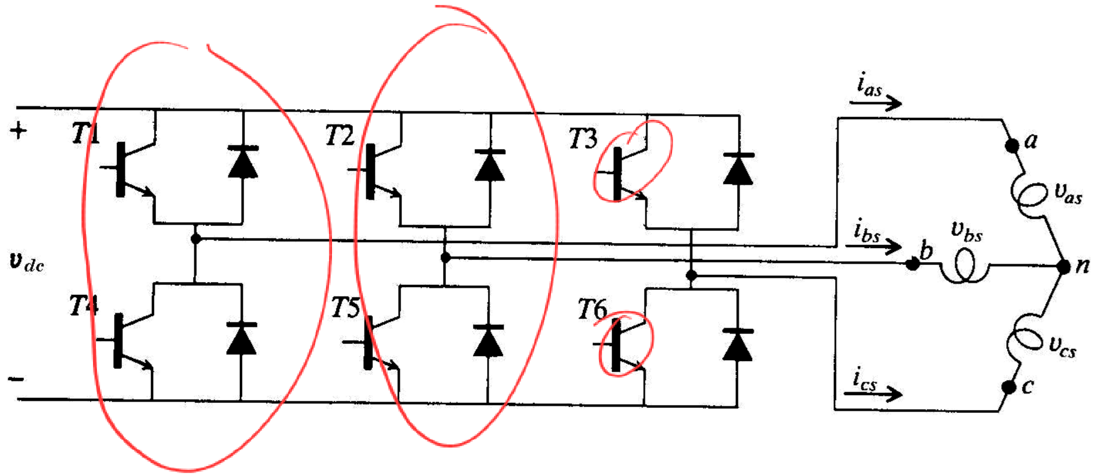
DC-AC Inverter



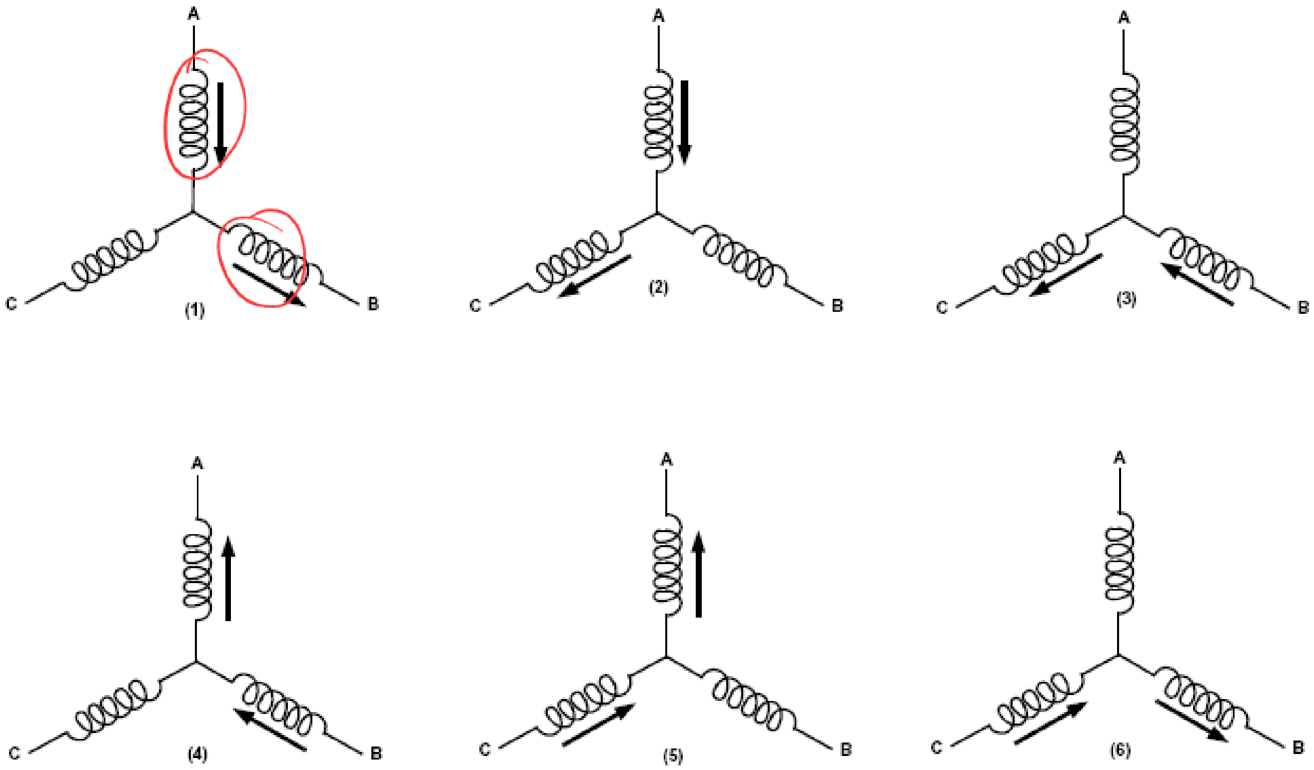
Hall sensor position sensors

120-Deg., 6-Step BLDC Motor Drive

Step	Rotor Position	Active Transistors
1	-30 to 30	T1, T5
2	30 to 90	T1, T6
3	90 to 150	T2, T6
4	150 to 210	T2, T4
5	210 to 270	T3, T4
6	270 to 330	T3, T5



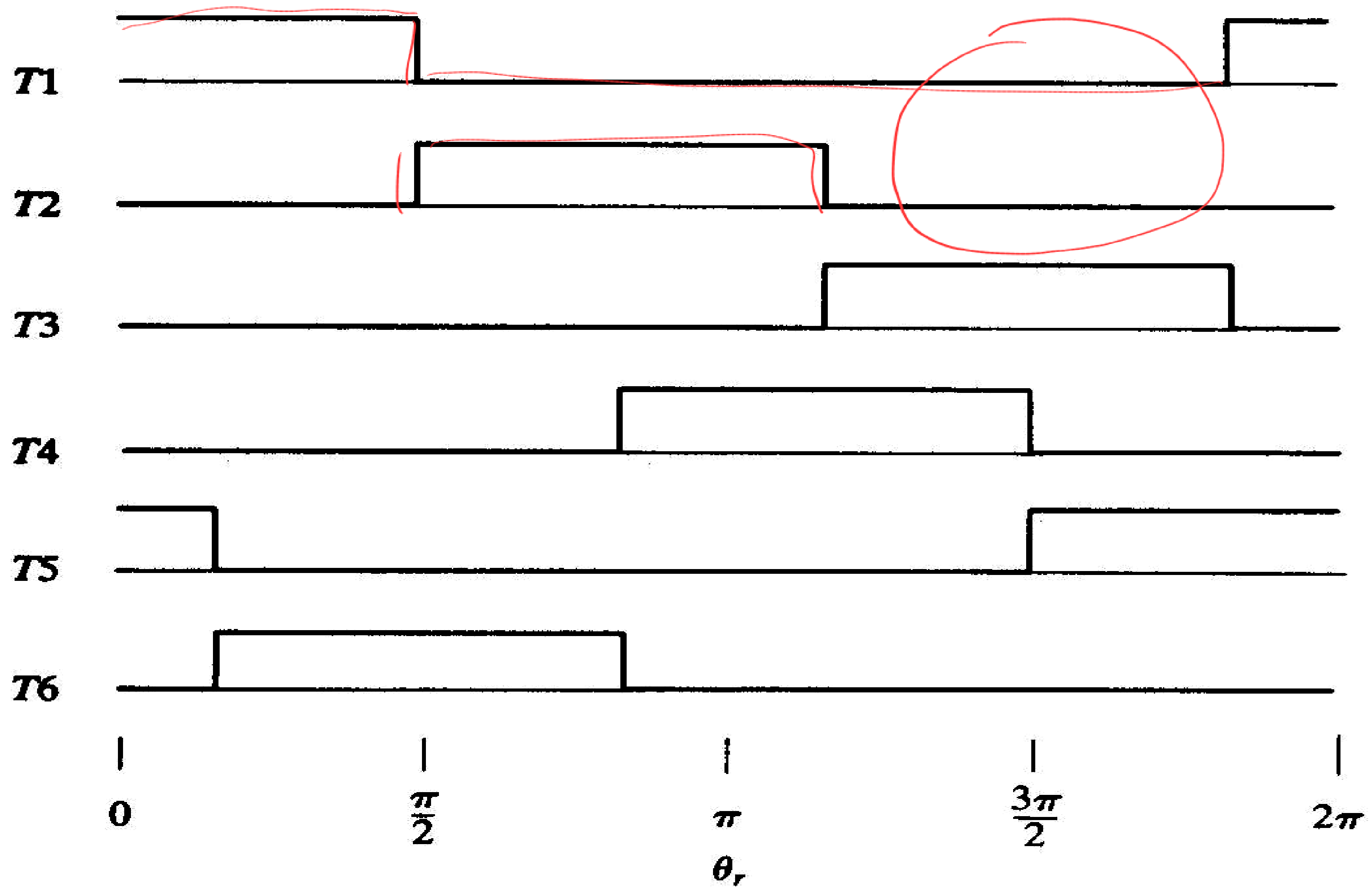
Produces magnetic field by only using 2 phases



3-Phase Brushless DC Motor Drive

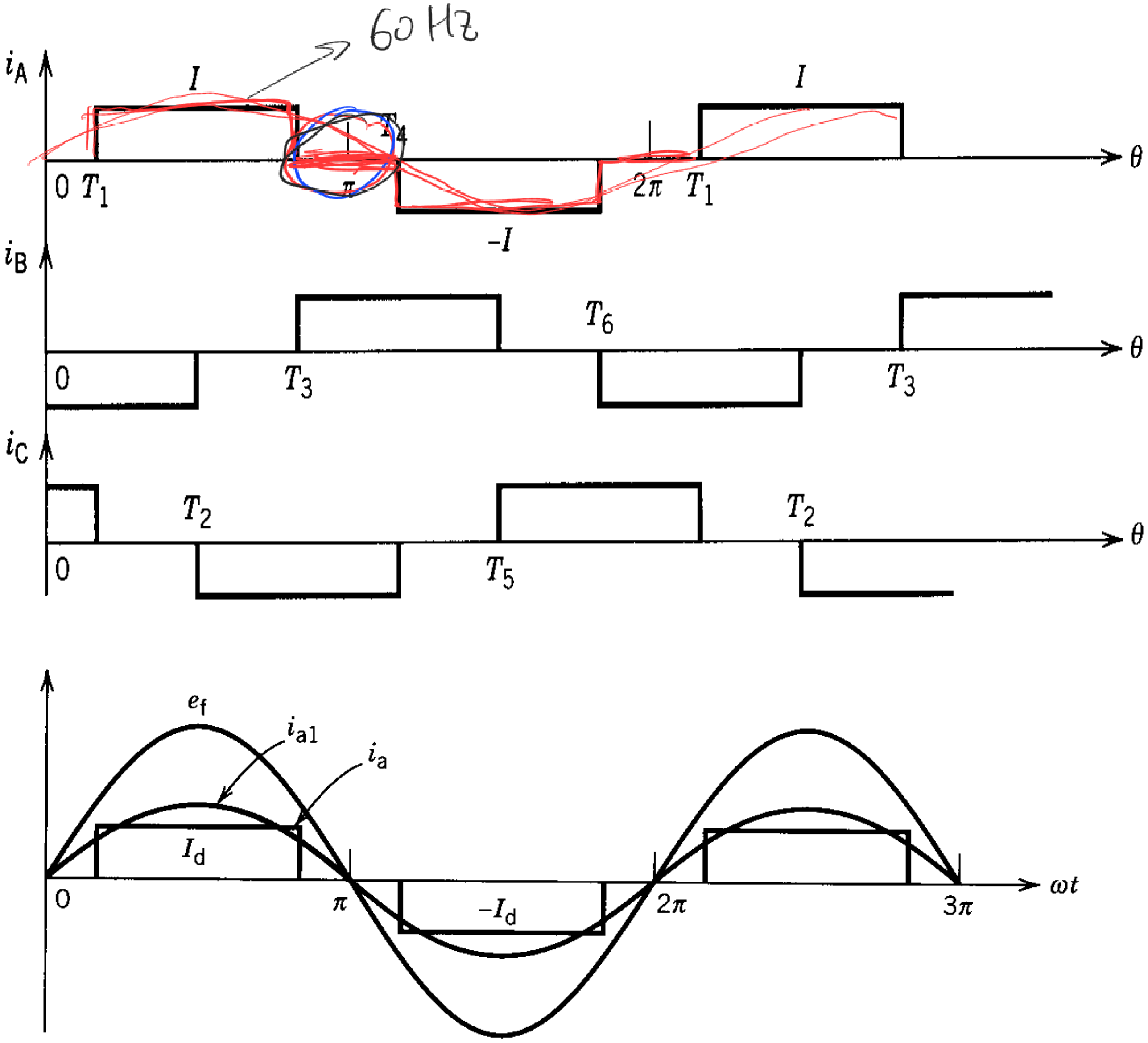
6-step, 120 deg. operation with PWM

Apply PWM to control the average voltage



Brushless DC Motor (Drive)

- Switch the transistors such that stator currents are always in phase with the rotor back emf

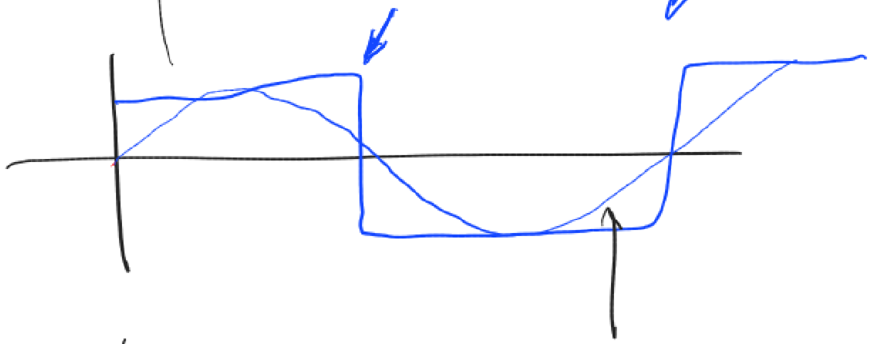


High DC-voltage utilization

$$E_f \sim \omega_r \Phi_f$$

$$T \sim \Phi_f I_{dc}$$

180 degree



100V

V_{DC} → square wave → V_{AC} → 60 V

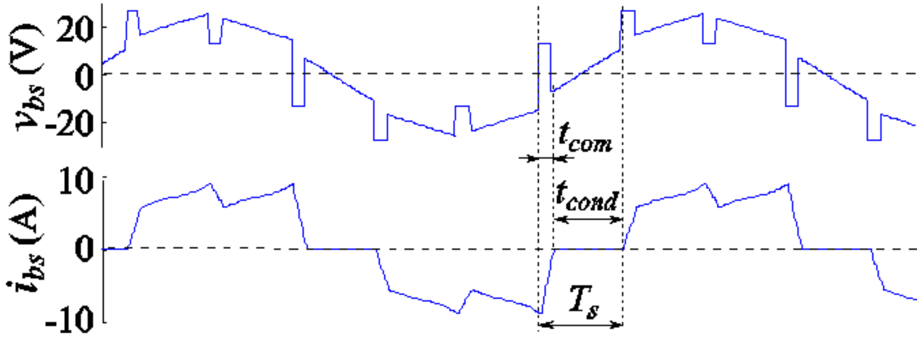
60Hz

→ 120 degree → V_{AC} → 40V

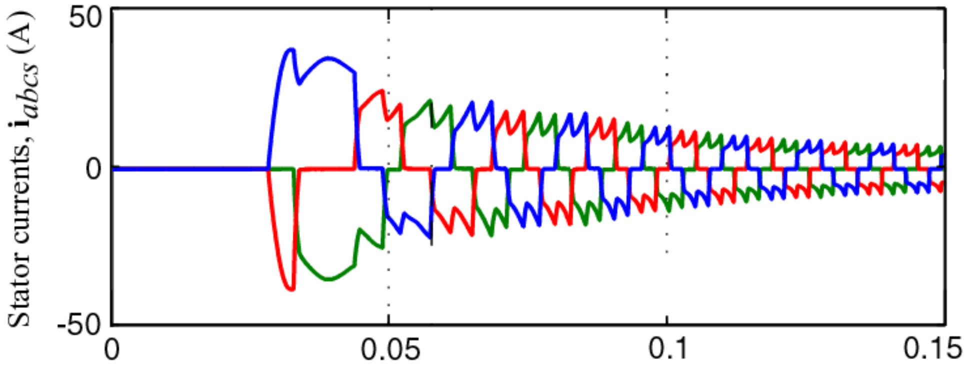
3-Phase Brushless DC Motor Drive

EECE 549

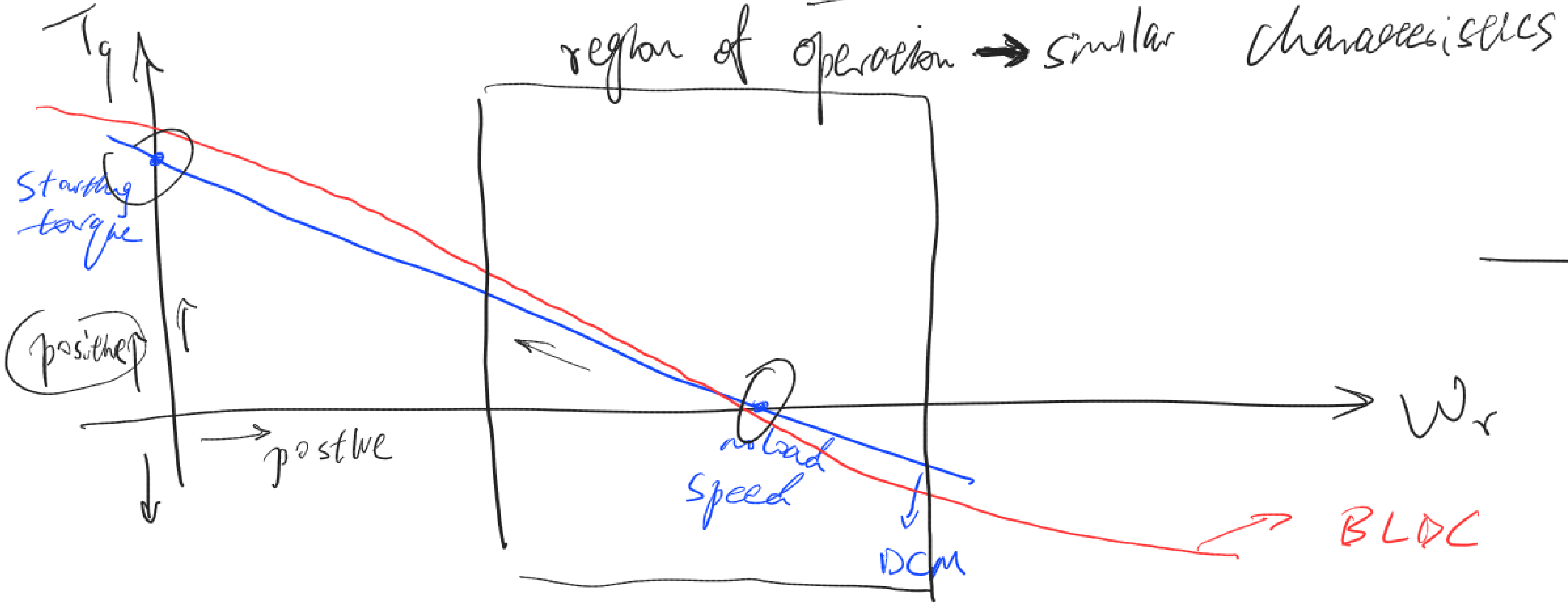
6-step, 120 deg. operation:
Typical steady state waveforms

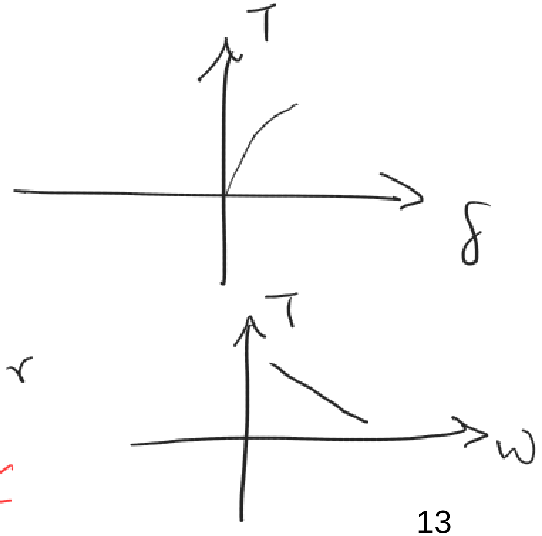


Start-up transient



- Torque-speed characteristic: PM Brushed DC vs. BLDC Motor



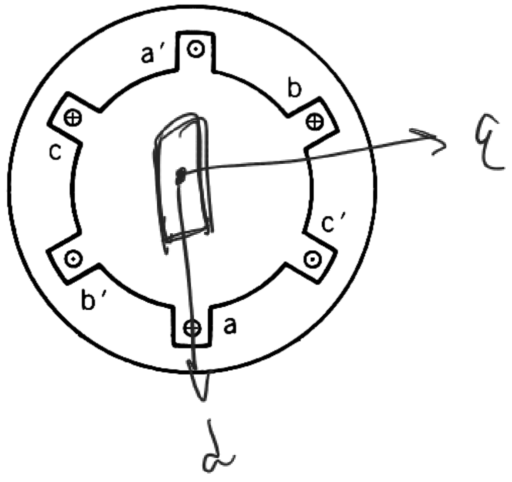


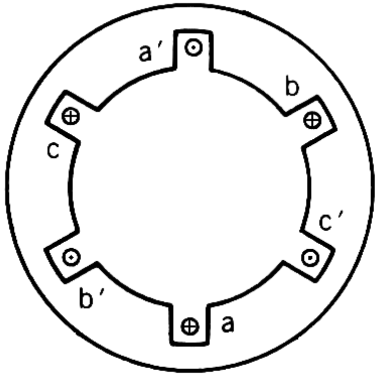
Principle of Reluctance Motors (Ch. 6.14)

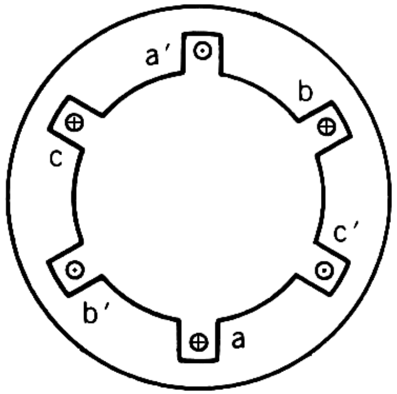
→ SM

Recall Variable Reluctance Motors

Rotor "is pushed" to take the position of minimal reluctance!







squirrel cage

Needs external startup: ① Damper winding → IM

② External ICE

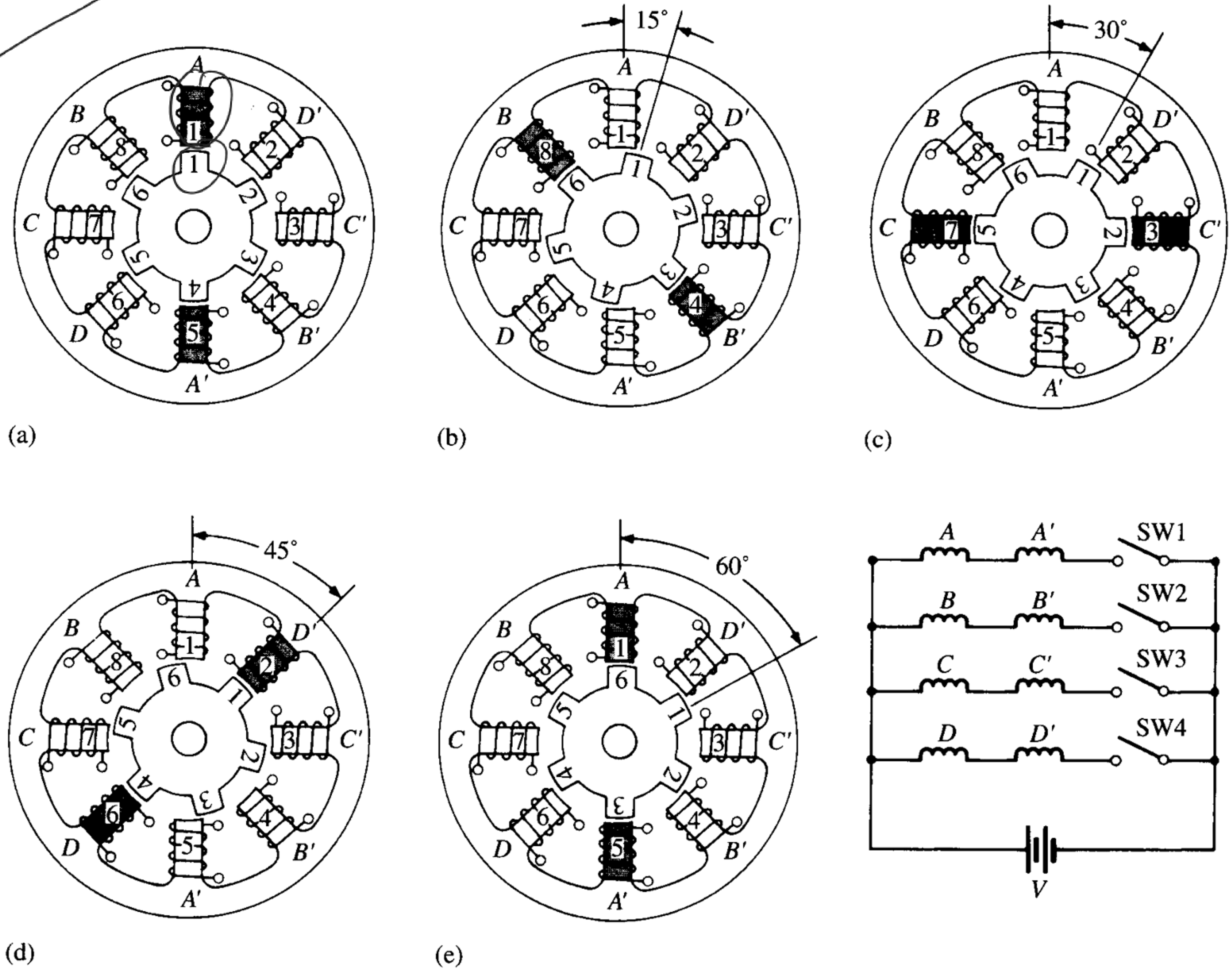
4-Phase, 8/6 Stepper Motor

→ reluctance machine

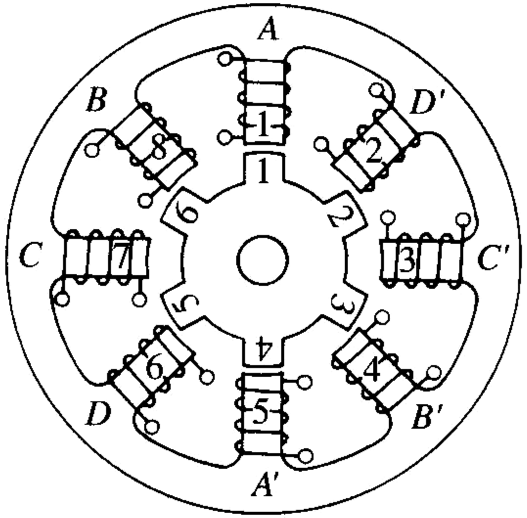
both stator and rotor have teeth

↓

Energize one pair of stator teeth at a time



4-Phase, 8/6 Stepper Motor



Terminology

N_{ST} - number of stator teeth

$STP = \dfrac{360^\circ}{N_{ST}}$ - stator tooth-pitch

N_{RT} - number of rotor teeth

$RTP = \dfrac{360^\circ}{N_{RT}}$ - rotor tooth pitch

$\theta_r = \Delta\theta \cdot N_{steps}$ - rotor position

$\Delta\theta = STP - RTP$ - step length

$f_{stepping} = \dfrac{N_{steps}}{\sec}$ - stepping frequency

$$\Delta\theta = \frac{360}{N_{ST}} - \frac{360}{N_{RT}} = \frac{N_{RT} - N_{ST}}{N_{ST} N_{RT}} 360^\circ$$

Speed

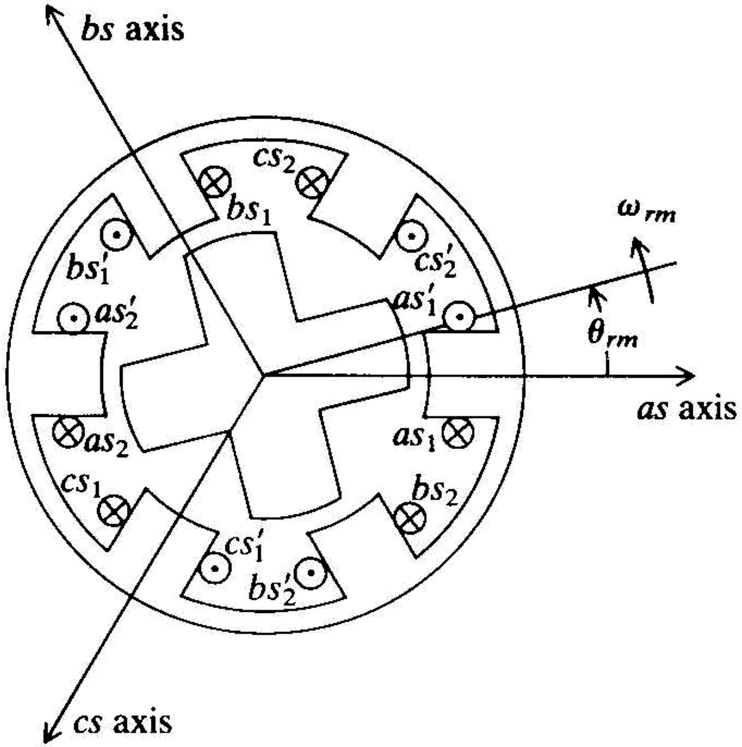
$$n = \frac{\Delta\theta \cdot f_{stepping}}{360} \; [\text{rev}/\sec]$$

$$n = \frac{\Delta\theta \cdot f_{stepping}}{6} \; [\text{rpm}]$$

$$\text{Resolution} = \frac{Steps}{\text{Rev.}} = \frac{360^\circ}{\Delta\theta}$$

Variable Reluctance Motors

Also known as Switched Reluctance Motors



What is the direction of rotation for as, bs, cs sequence ?

2-pole, 3-phase, 6/4 - teeth

$$N_{ST} = 6 \quad N_{RT} = 4 \qquad N_{ST} \neq N_{RT}$$

Tooth Pitch

$$STP = \frac{360^\circ}{N_{ST}} = 60^\circ$$

$$RTP = \frac{360^\circ}{N_{RT}} = 90^\circ$$

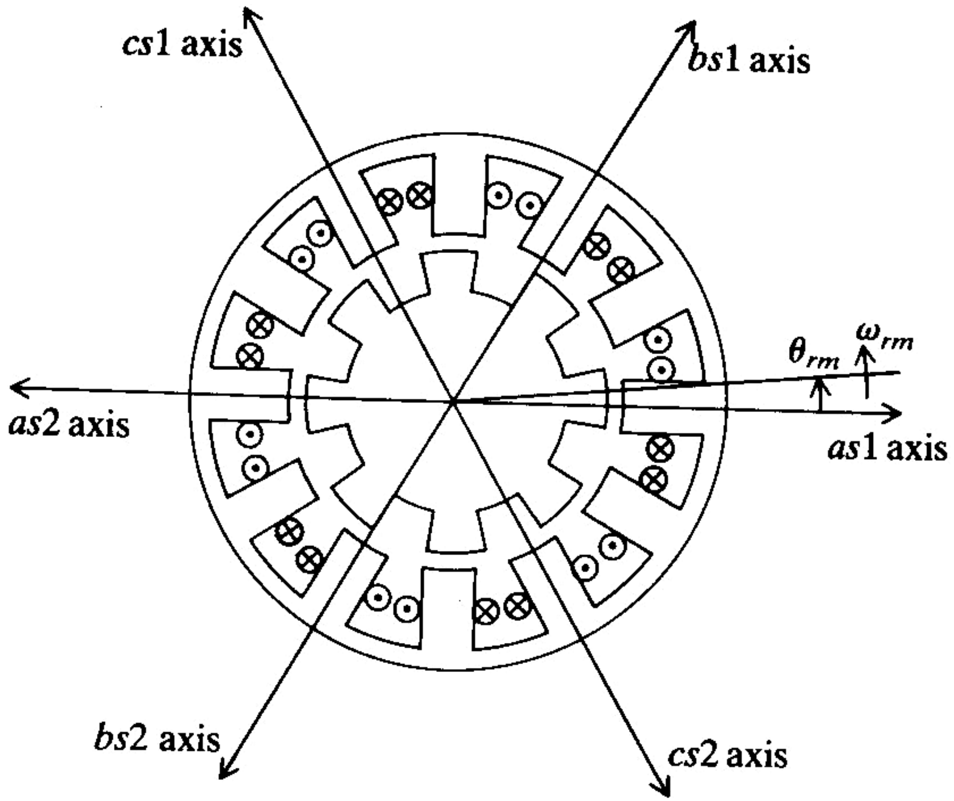
Step Length (SL)

$$\Delta\theta = \frac{RTP}{N_\phi} = \frac{360^\circ}{N_{RT} N_\phi} = 30^\circ$$

$$= \left| RTP - STP \right| = 30^\circ$$

Variable Reluctance Motors

4-pole, 3-phase, 12/8 - teeth



What is the direction of rotation for as, bs, cs sequence ?

$$N_{ST} = 12 \quad N_{RT} = 8 \qquad N_{ST} \neq N_{RT}$$

Tooth Pitch

$$STP = \frac{360^\circ}{N_{ST}} = 60^\circ$$

$$RTP = \frac{360^\circ}{N_{RT}} = 45^\circ$$

Step Length (SL)

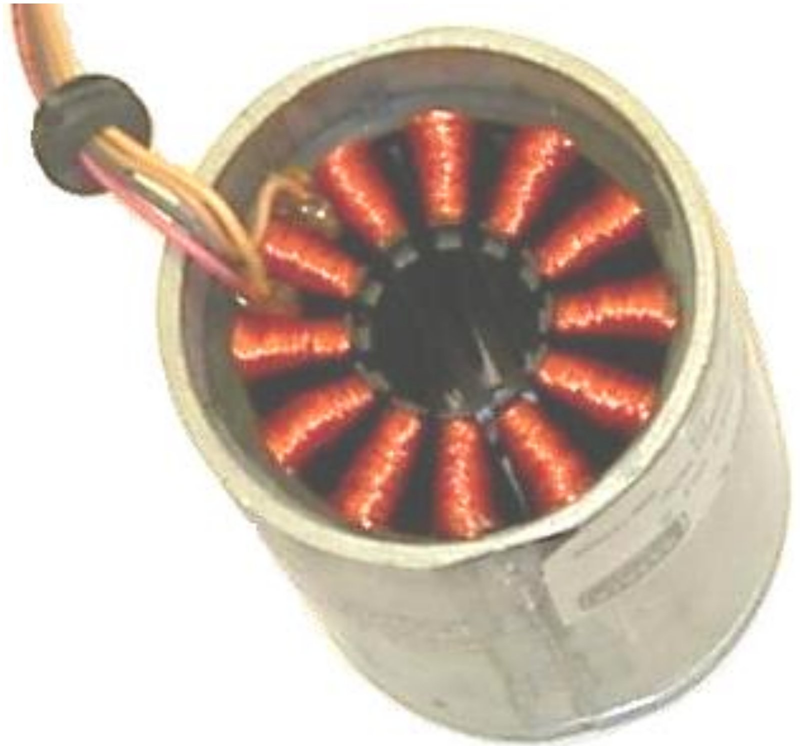
$$\Delta\theta = \frac{RTP}{N_\phi} = \frac{360^\circ}{N_{RT} N_\phi} = 15^\circ$$

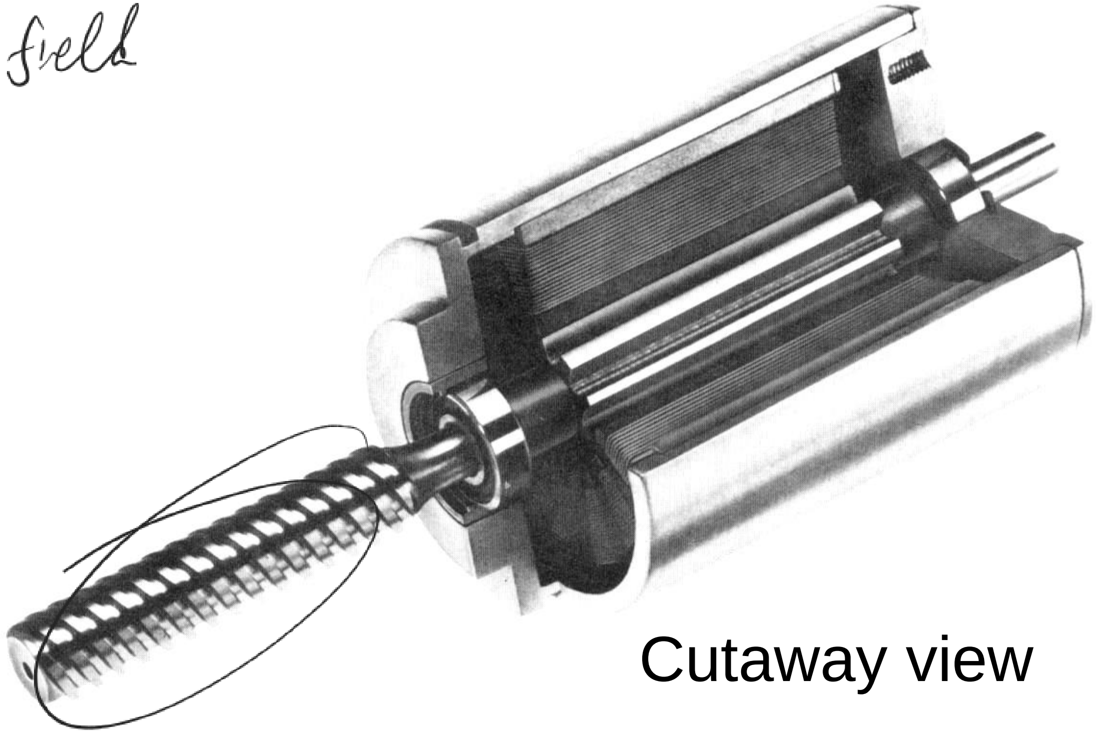
$$= \left| RTP - STP \right| = 15^\circ$$

12/8 Variable Reluctance Motor

Con: - Low torque

Pro: - no rotor field
- no PM



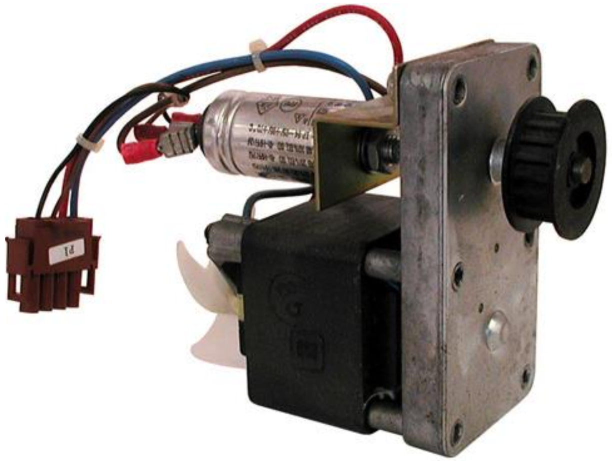


Cutaway view

Single Phase AC Motors (Ch. 7.1 & 7.2)

Important Topics and Concepts

- Principle of operation of Single-phase Induction Motors
- Types commonly used Single-phase Induction Motors: Split-phase, Capacitor-Run, Shaded-Pole Motors
- Characteristics and range of applications
- Universal motor

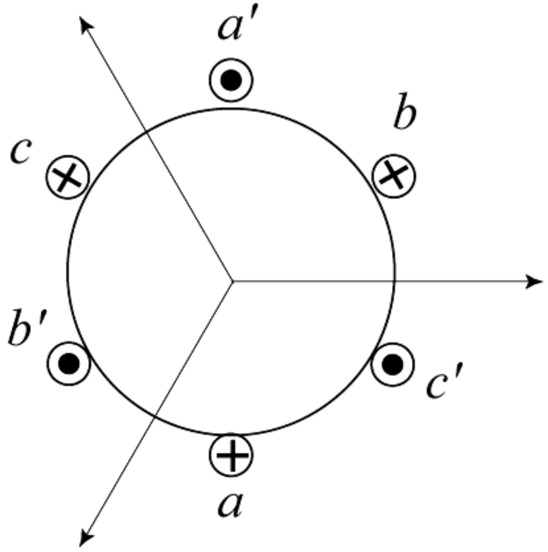


- Less efficient
- Low power
- Low maintenance
- Very inexpensive
- Often used capacitors & gearheads

Single-Phase Induction Motors

$120°$

3-phase system



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

Rotating Magnetic Field

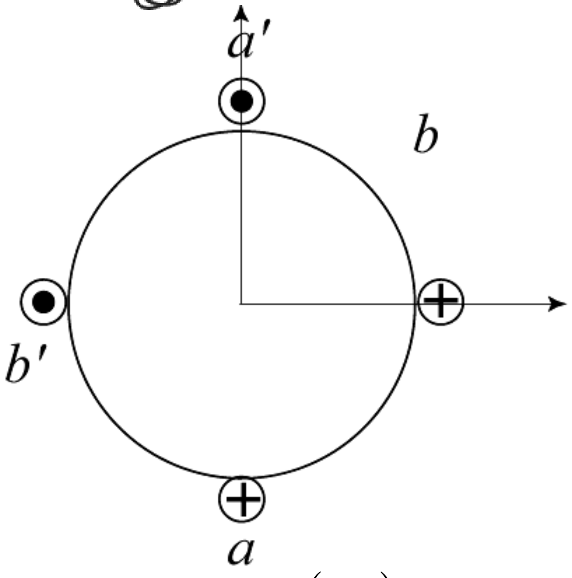
1. Phase shifted currents
2. Displaced windings

$$\mathbf{F}_{net} = F_{mag} \angle \theta_e$$

$\omega_e t$

$90°$

2-phase system



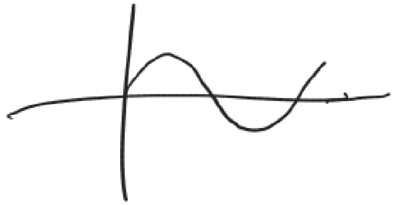
$$i_a = I_m \sin(\omega_e t)$$
$$i_b = I_m \sin(\omega_e t - 90^\circ)$$

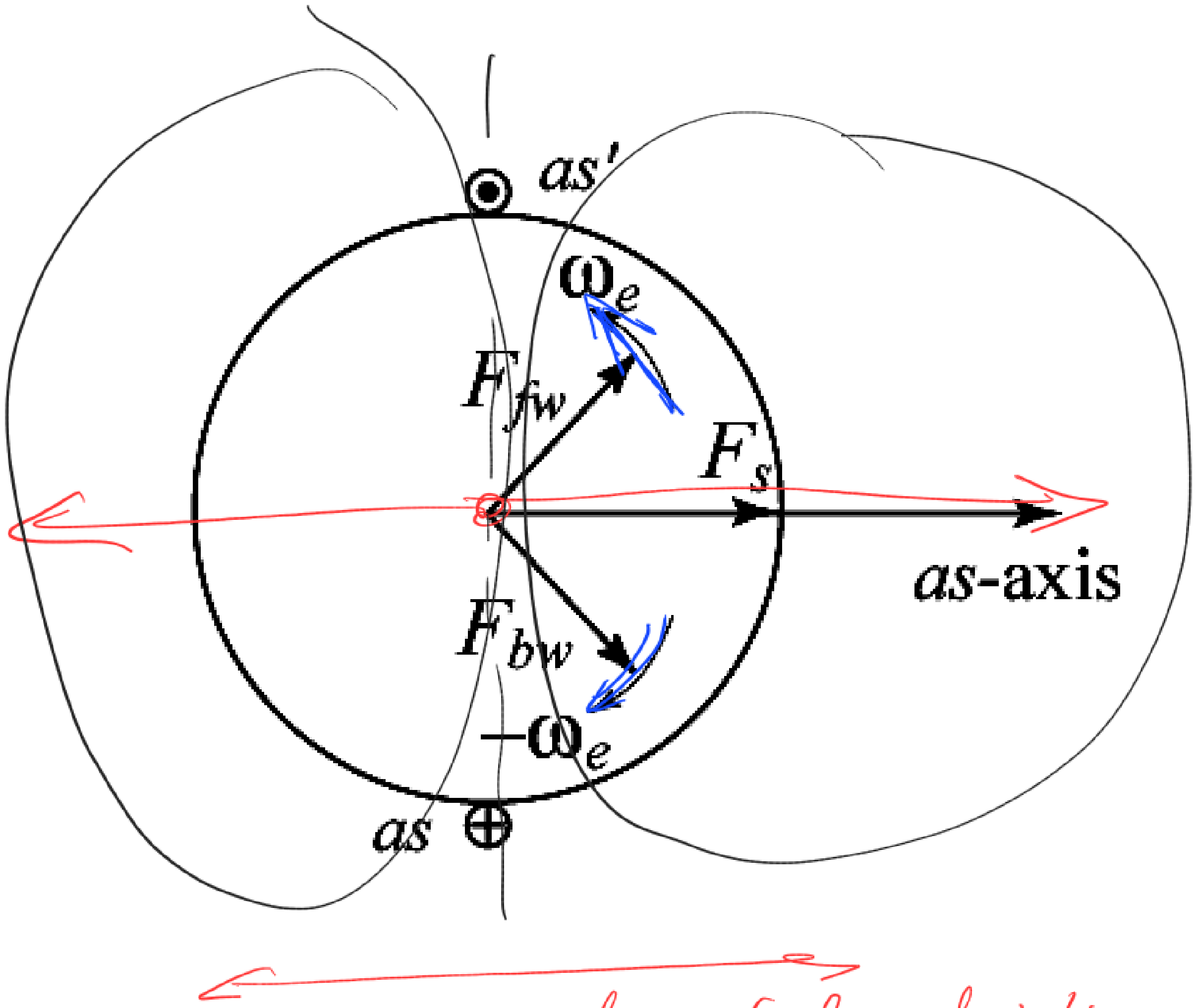
In some small applications (under 1 or 2 kW)
3-phase or 2-phases are not always available !

How can we produce rotating magnetic field with just one phase ?

Single-Phase Induction Motors

Pulsating magnetic field $\mathbf{F}_s = \mathbf{F}_{fw} + \mathbf{F}_{bw}$





Flux pulsating left and right

CCW CW

Pulsating field $\mathbf{F}_s$ can be viewed as two magnetic fields $\mathbf{F}_{fw}$ and $\mathbf{F}_{bw}$ of ½ strength and rotating in opposite directions

Forward component

$$\mathbf{F}_{fw} = \frac{1}{2} F_m \angle \theta_e$$

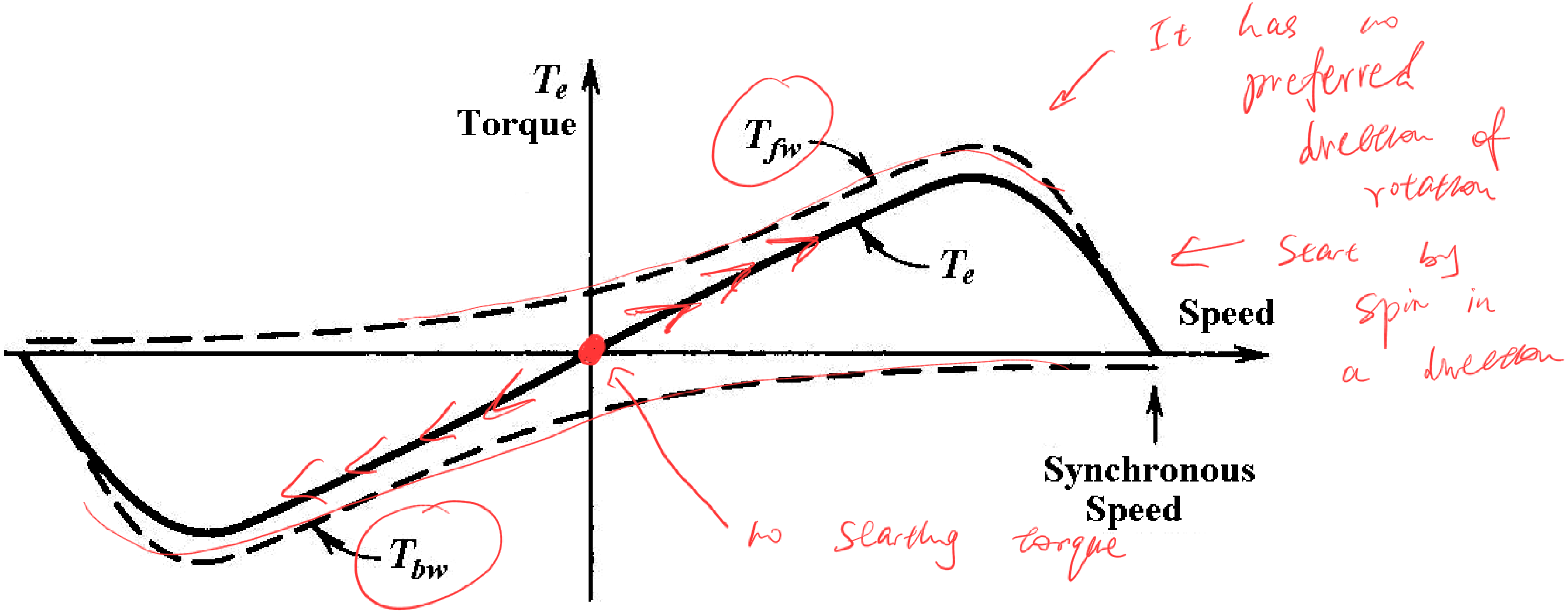
Backward component

$$\mathbf{F}_{bw} = \frac{1}{2} F_m \angle -\theta_e$$

Torque – Speed (Slip) Characteristic

Recall 3-phase IM $T_e = 3\frac{P}{2}\cdot\frac{|V_{th}|^2}{\omega_e}\cdot\frac{(R_2'/s)}{(R_{th}+R_2'/s)^2+(X_{th}+X_2')^2}$

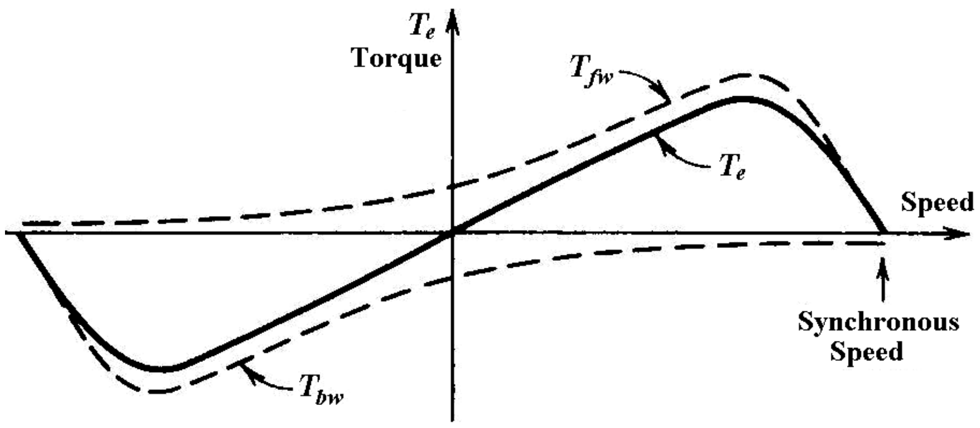
Recall single-phase IM $T_{e,net} = T_{fw} - T_{bw}$ (Forward minus Backward)



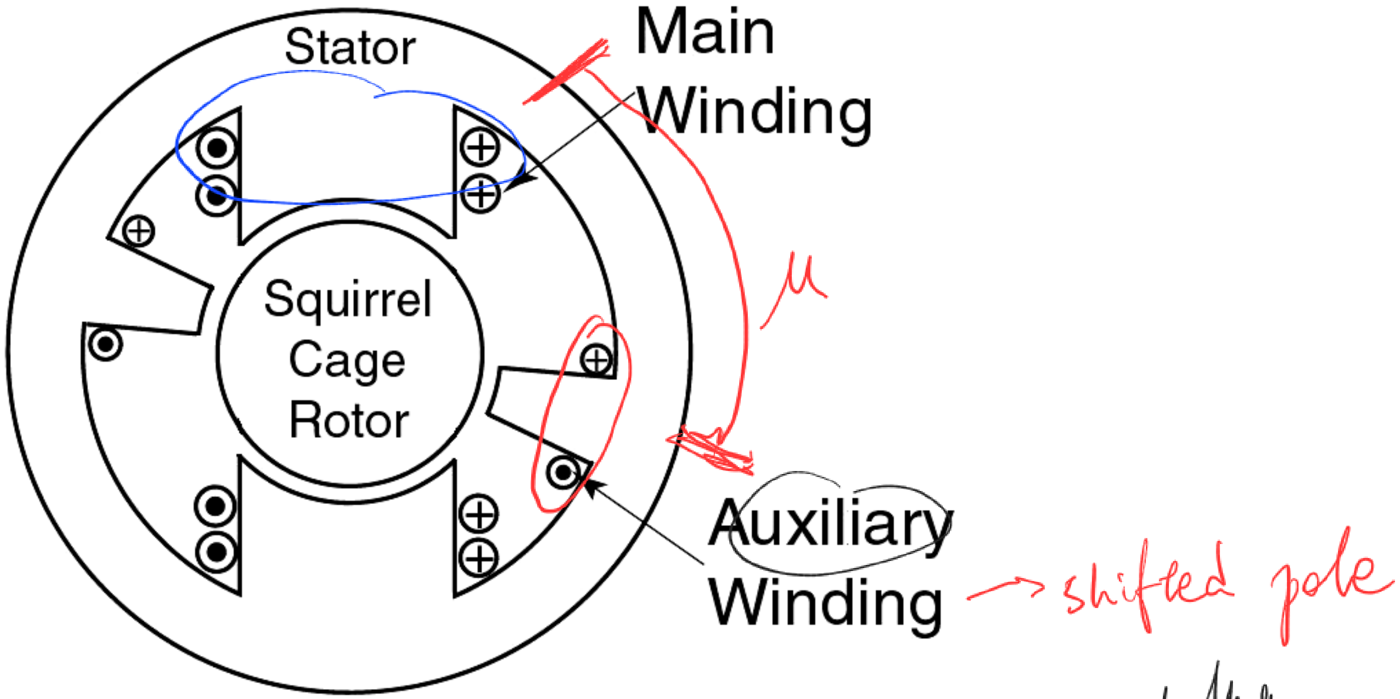
Split-Phase Induction Motors

Recall single-phase IM with one stator winding

No starting torque!

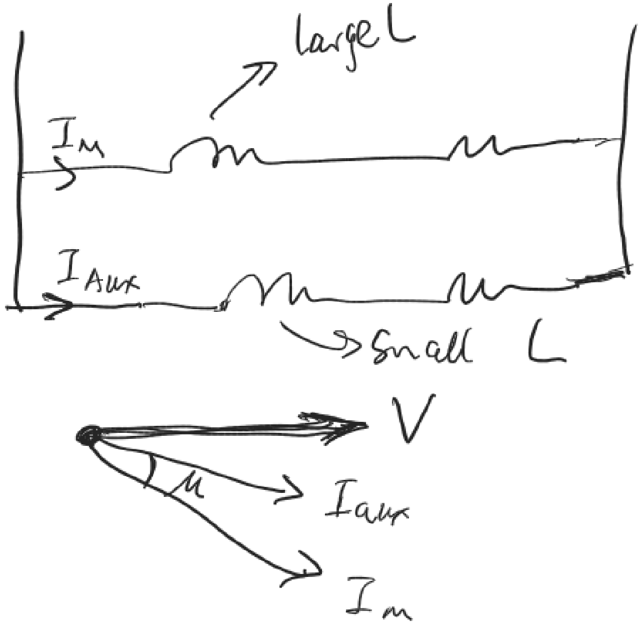


Use auxiliary winding (pole)

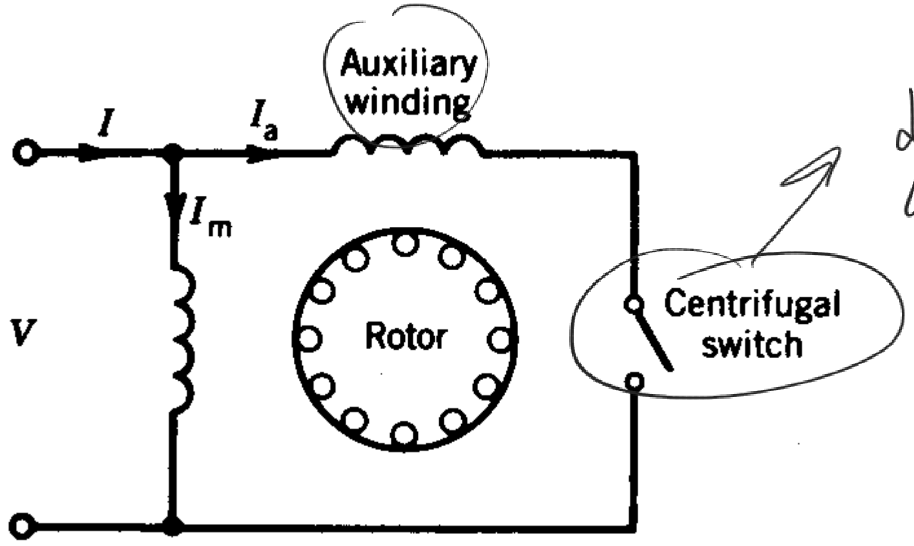


First activate aux winding, then the main winding

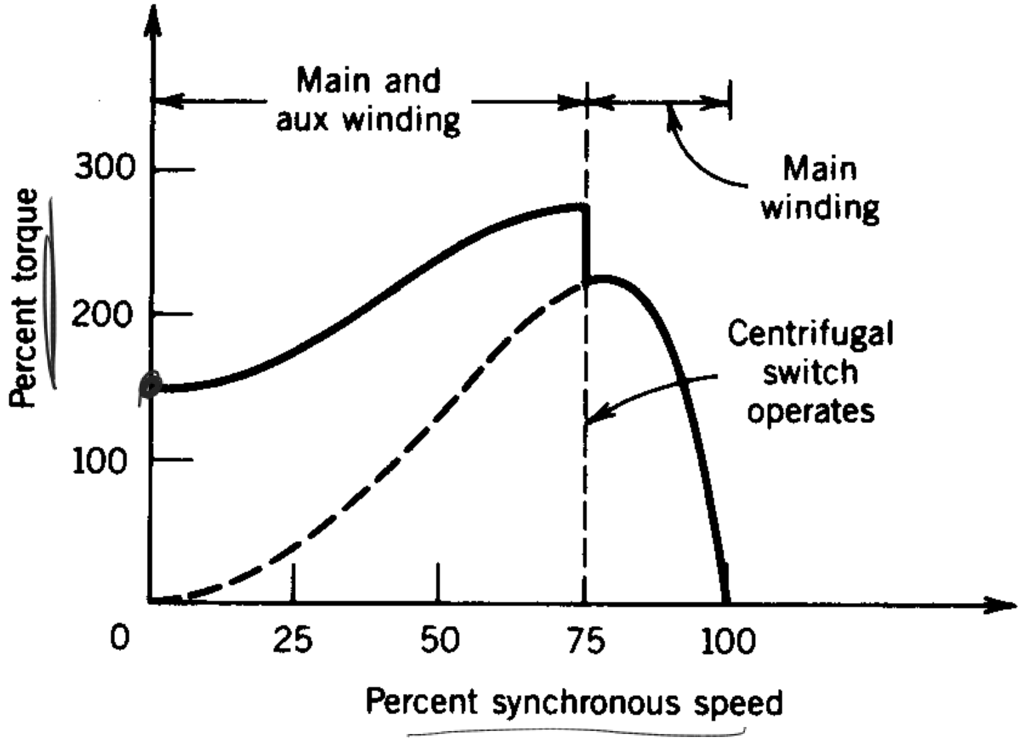
Shift phase of the current in auxiliary winding



Split-Phase Motors



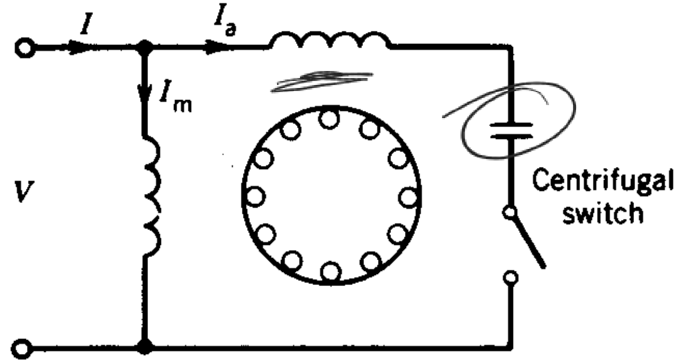
disconnects aux winding

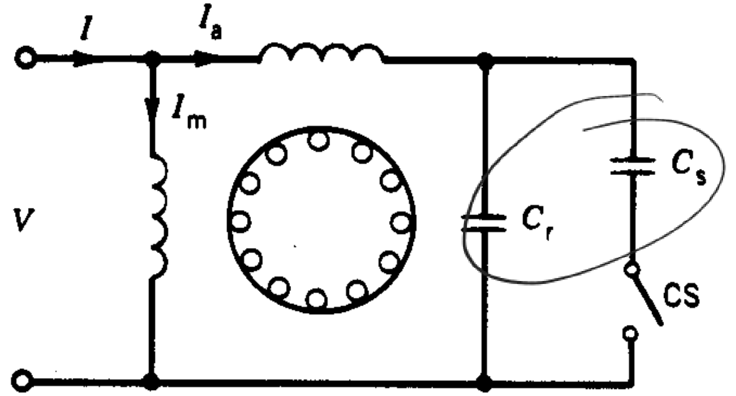


what else changes current phase?

↳ capacitor

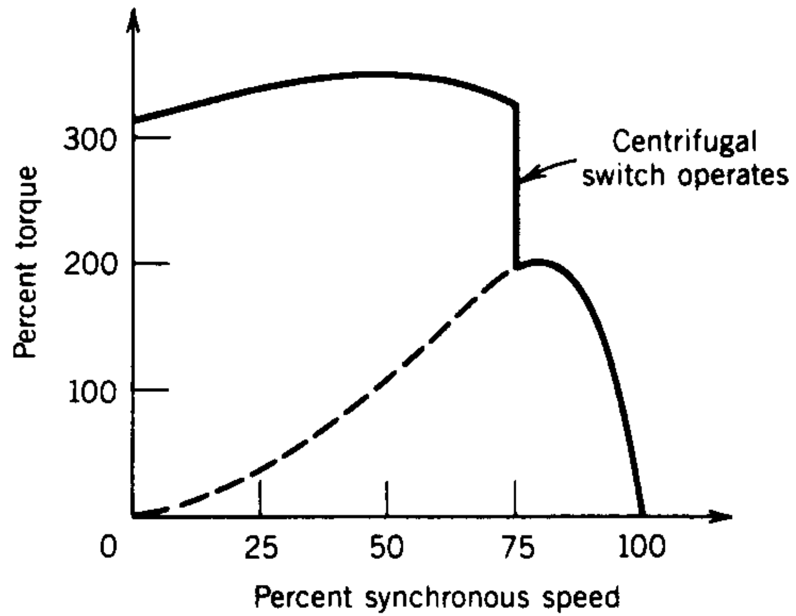
Capacitor-Start/Run Motors

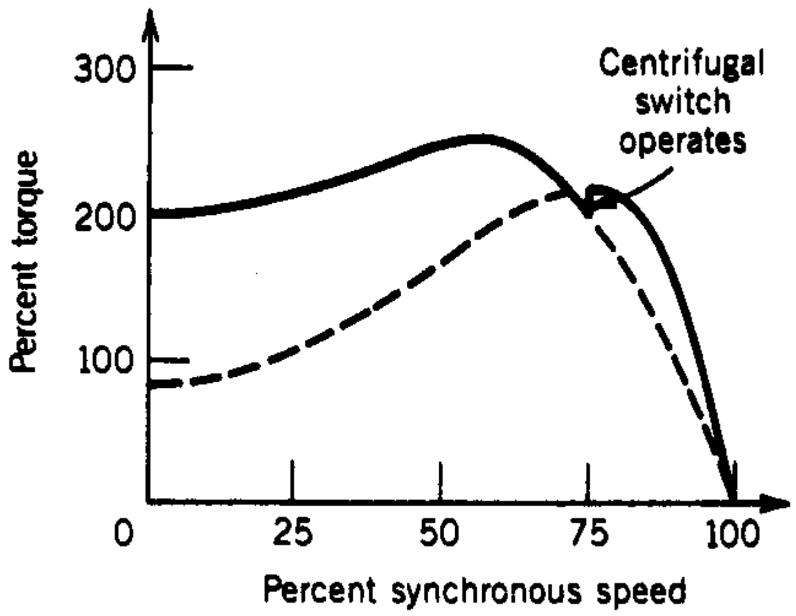




Lagging

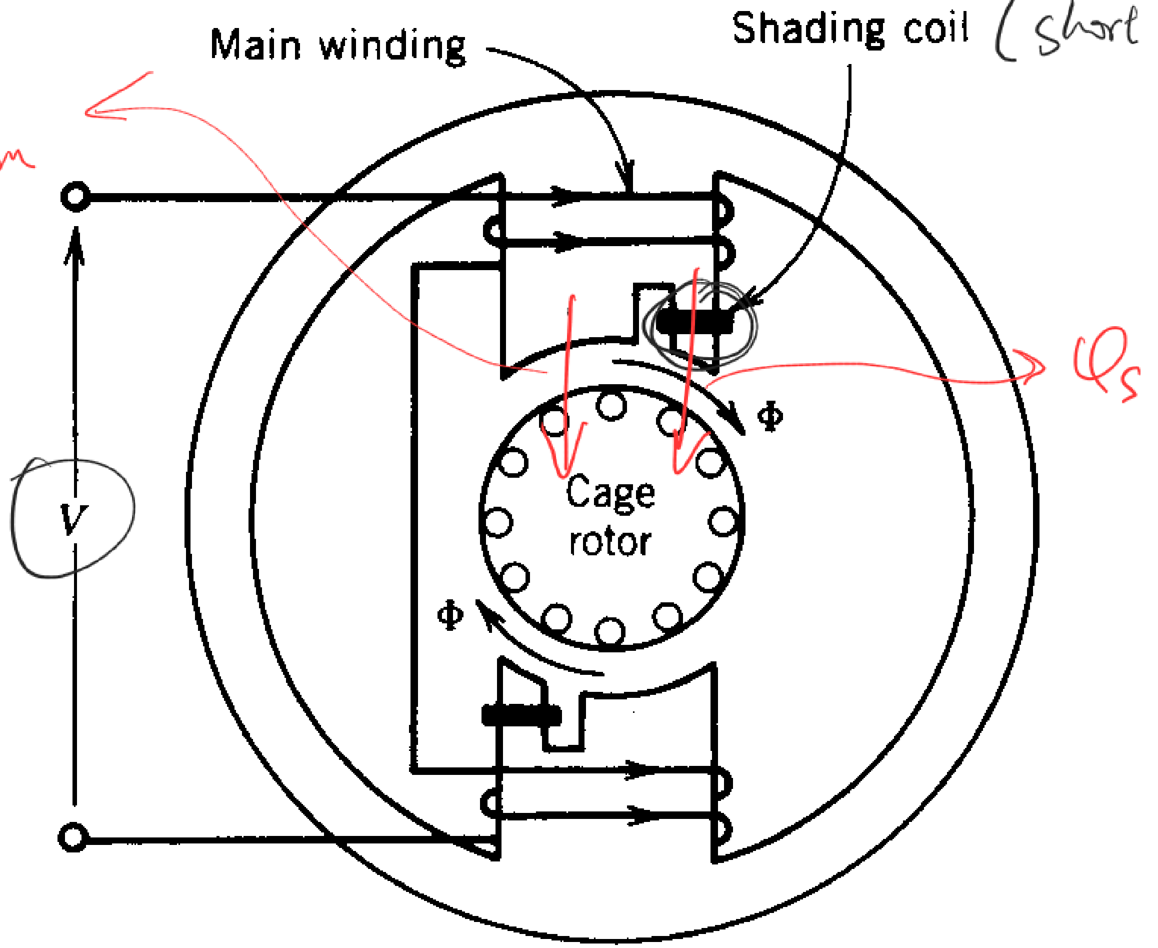
Leading

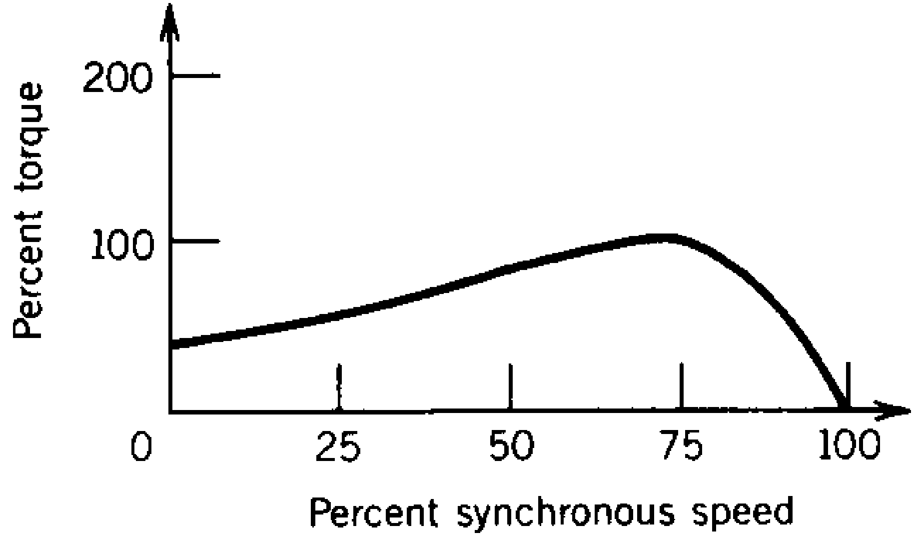




Shaded-Pole Motors → split one pole in 2 parts

- In very small applications, under 50 W
- Very inexpensive
- High slip, Low efficiency





φ_s and φ_m are delayed

φ_m

φ_s

ω_r, T_e

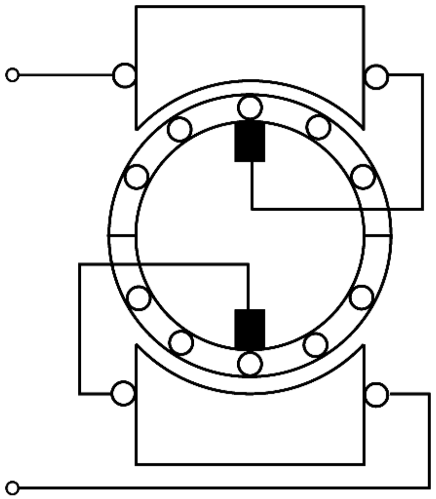
Single-Phase Induction Motors

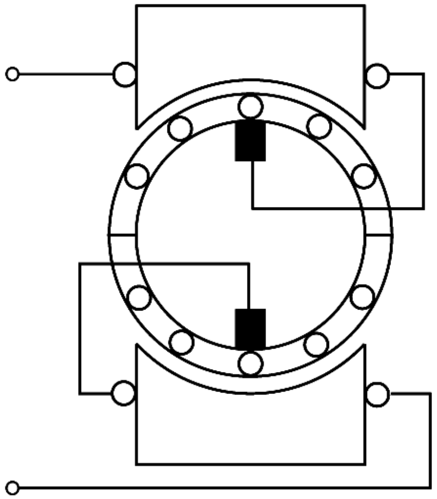
Low efficiency

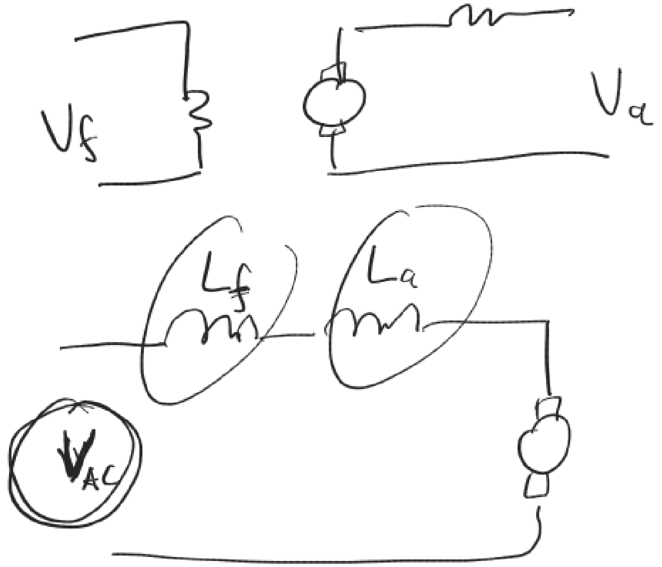
Type of Motor	Torque as % of Rated Torque		Rated Load		Horsepower Range
	Starting	Breakdown	Power Factor	Efficiency	
Split-phase (resistance-start)	100–250	Up to 300	50–65	55–65	1/20–1
Capacitor-start	250–400	Up to 350	50–65	55–65	1/8–1
Capacitor-run	100–200	Up to 250	75–90	60–70	1/8–1
Capacitor-start, capacitor-run	200–300	Up to 250	75–90	60–70	1/8–1
Shaded-pole	40–60	140	25–40	25–40	1/200–1/20

Single-Phase Universal Motors → series or shunt DCM

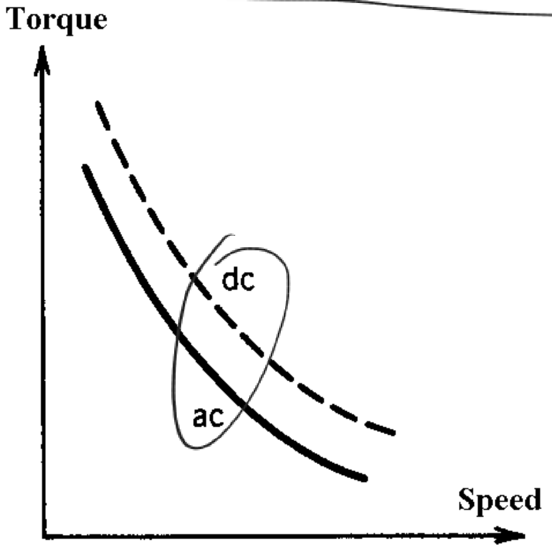
Recall Series (Brushed) DC Motor







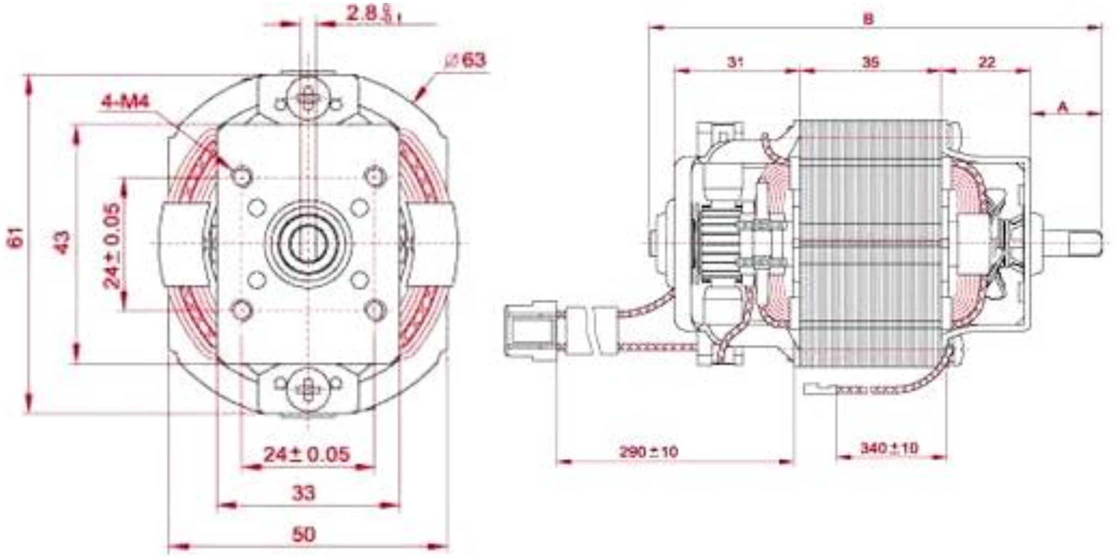
AC versus DC Excitation

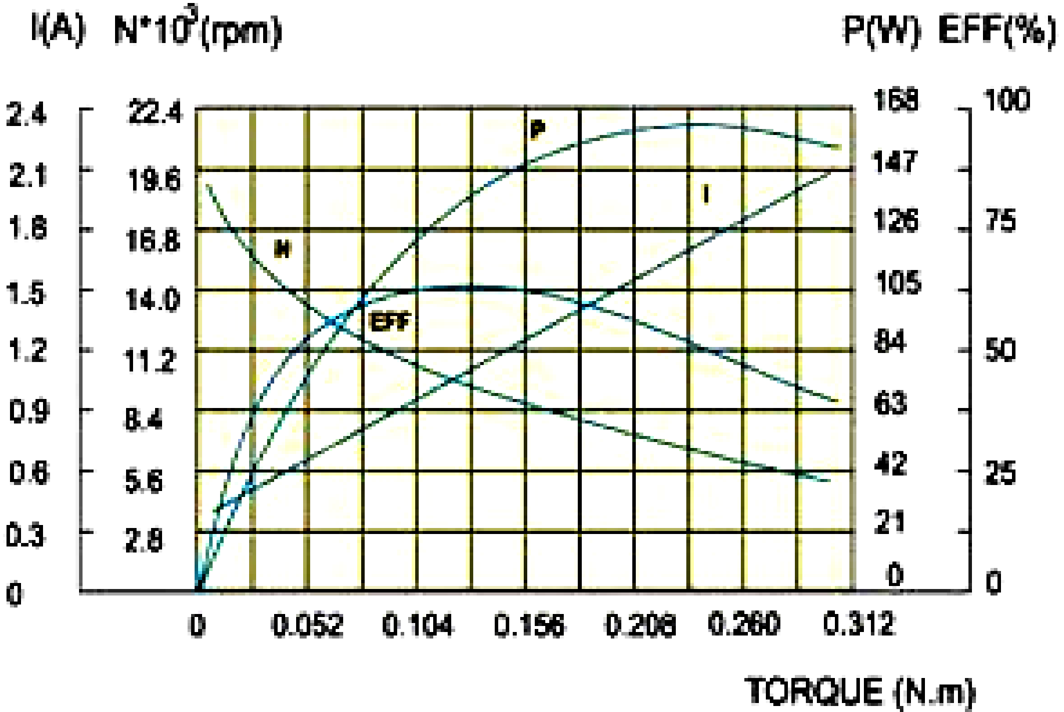


Fractional horsepower applications
Domestic appliances such as:
- Portable tools, drills, mixers, blenders, vacuum cleaners, etc

Operate at high speeds
(1500 – 10,000 rpm)

Single-Phase Universal Motors





Fractional horsepower applications

Domestic appliances such as:

Portable tools, drills, mixers, blenders, vacuum cleaners, etc

Operate at high speeds

(1500 – 10,000 rpm)

ELEC 342: Electromechanical Energy Conversion

Looking ahead…

- Exam review