ME133 Lecture 14

3/2/23

Last time:

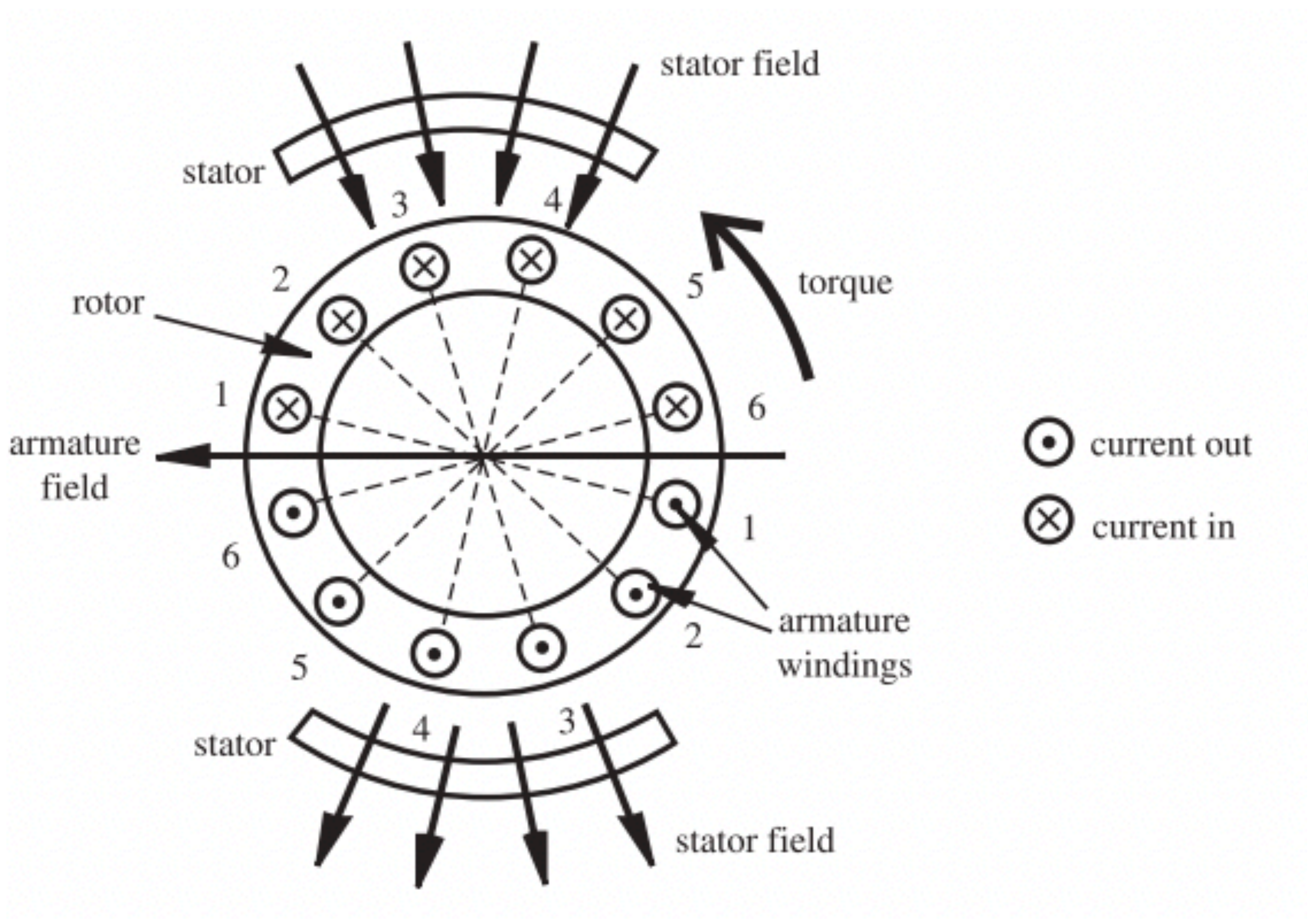
> DC Motors

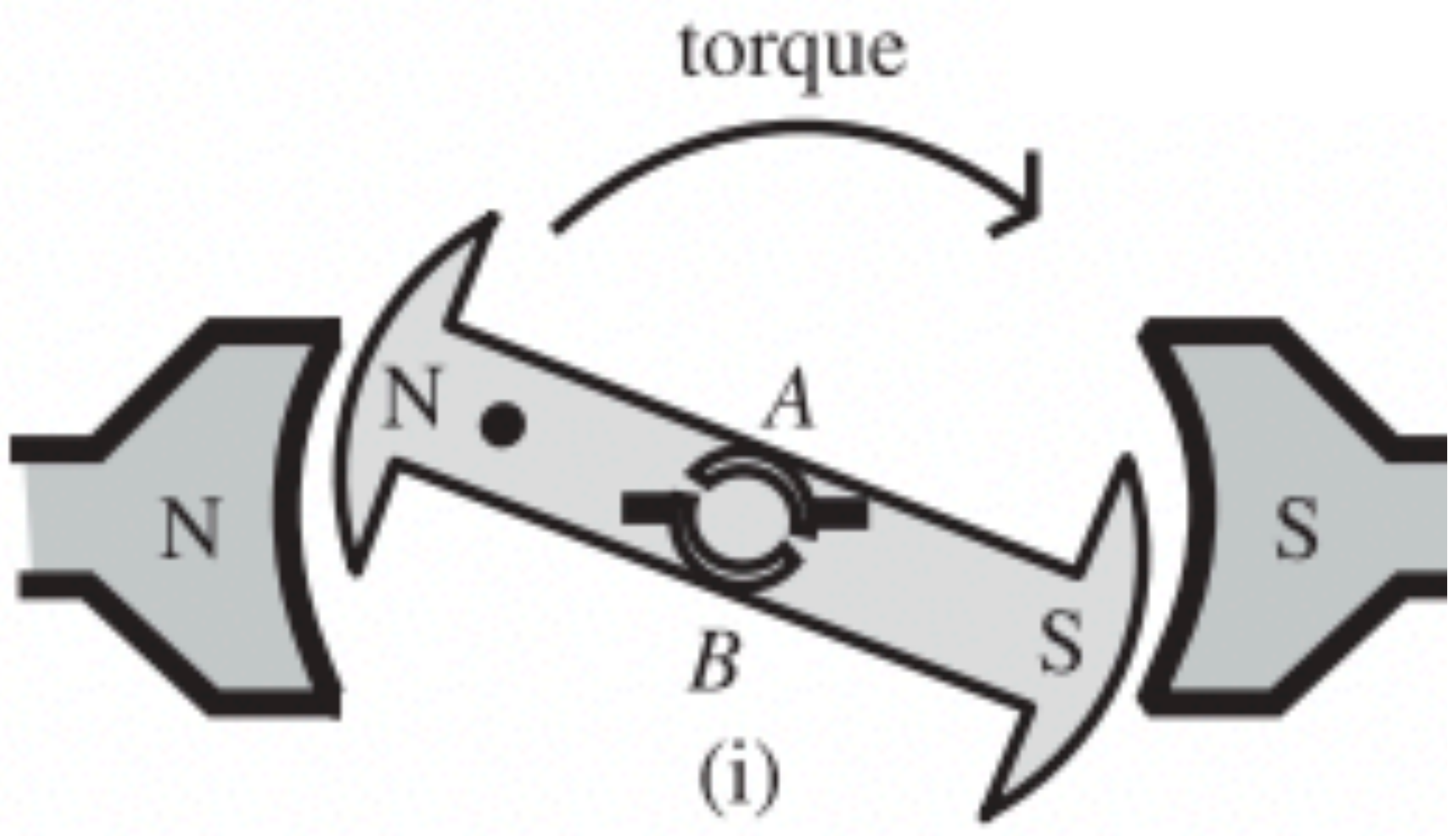
Today:

> DC Motors + Stepper motors

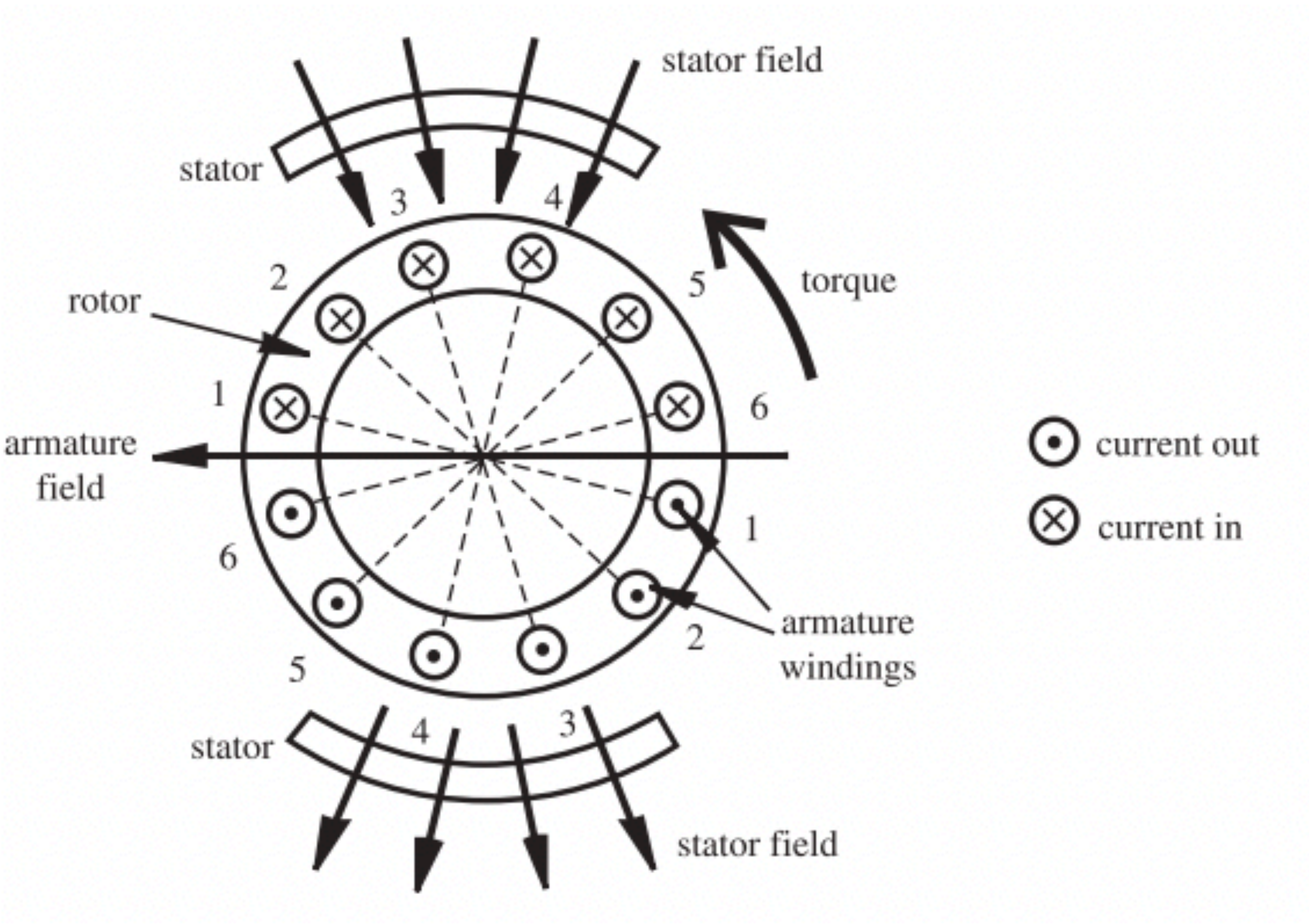
DC Motors: Working Principle

Torque is produced by an electric motor through the interaction of either stator fields and armature currents or stator fields and armature fields.



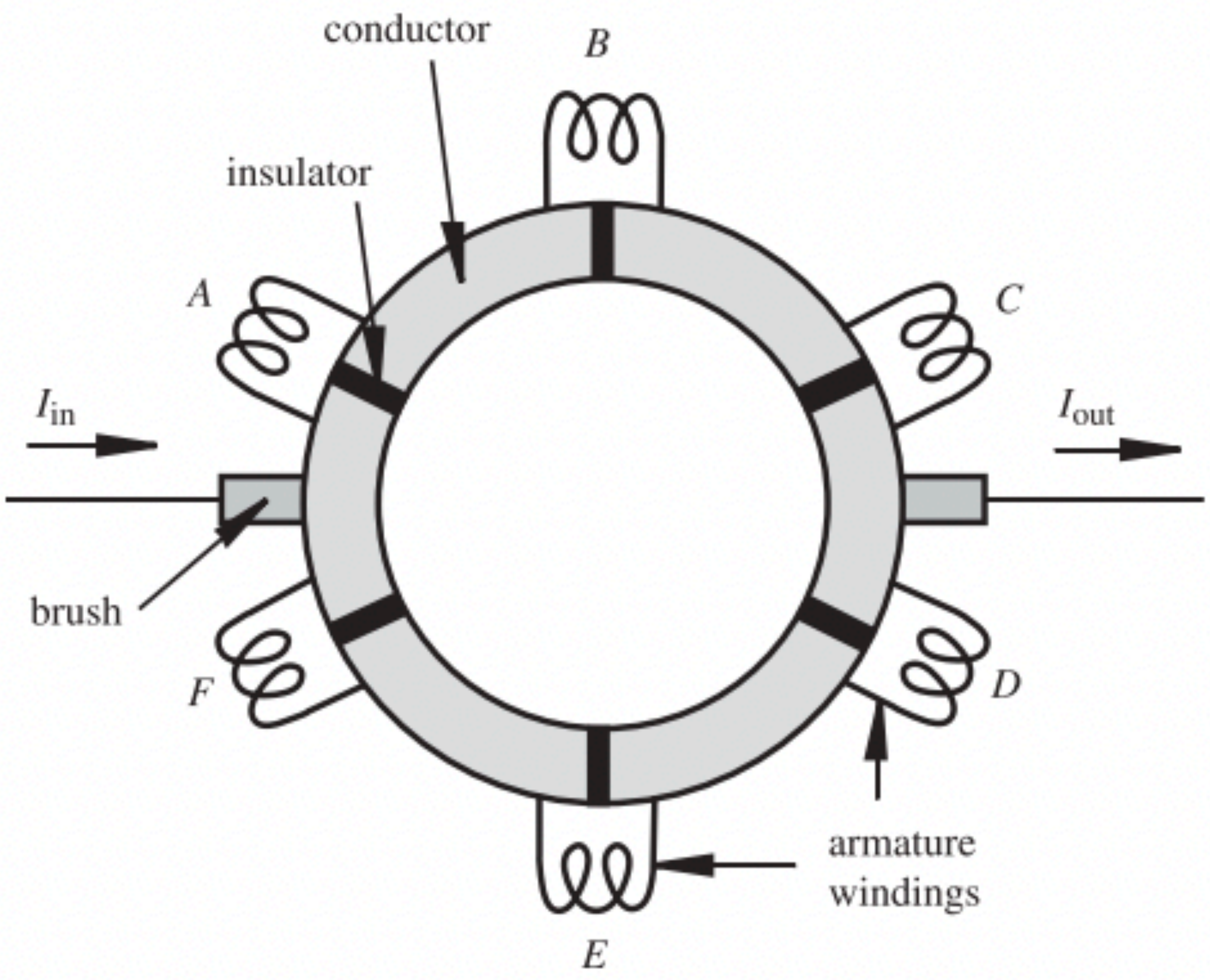


DC Motors: Working Principle - stator field/armature currents



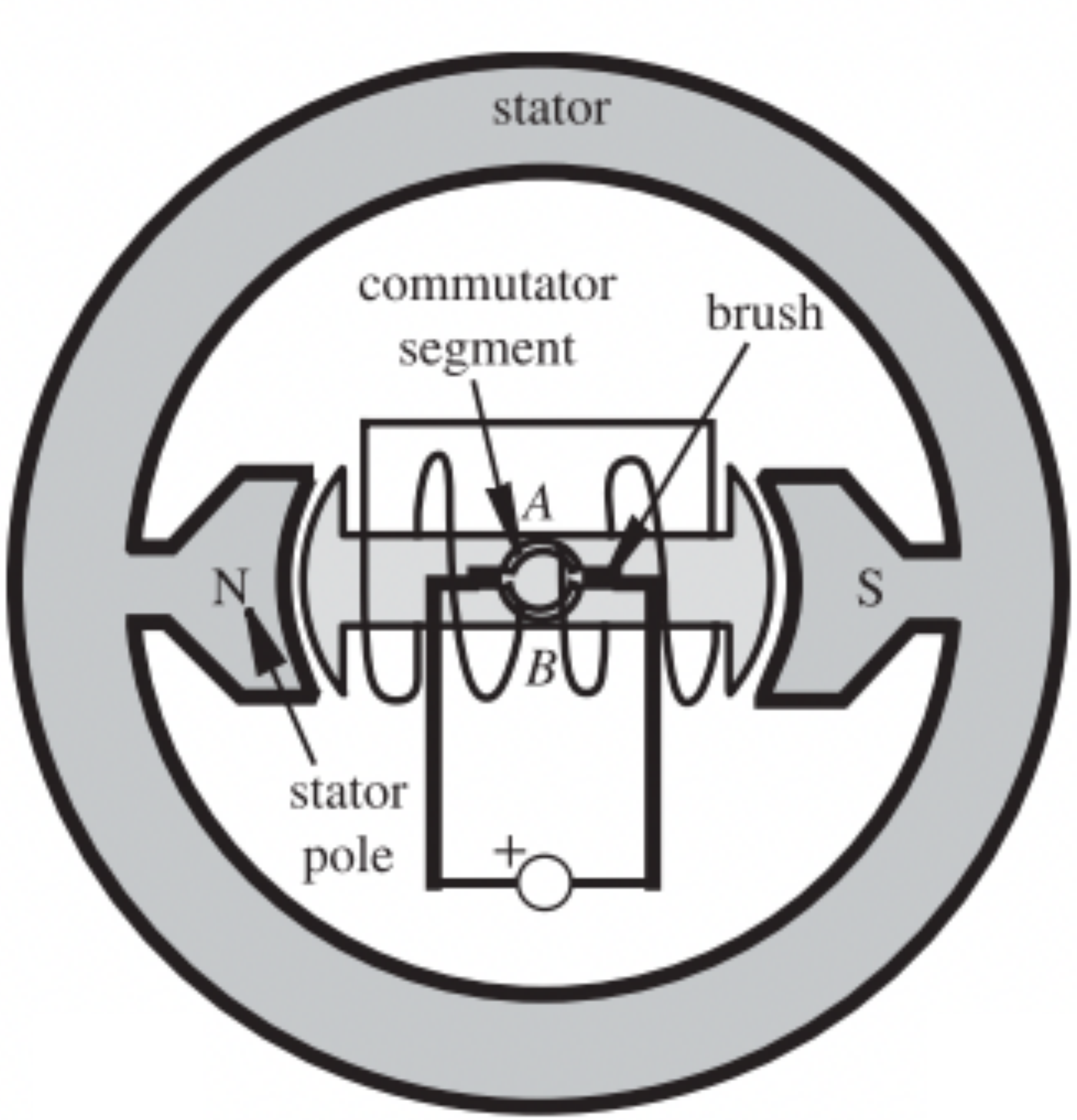
DC motor with six armature windings

DC Motors: Working Principle - stator field/armature currents



Electric motor six-winding commutators

DC Motors: Working Principle - stator/rotor magnetic fields

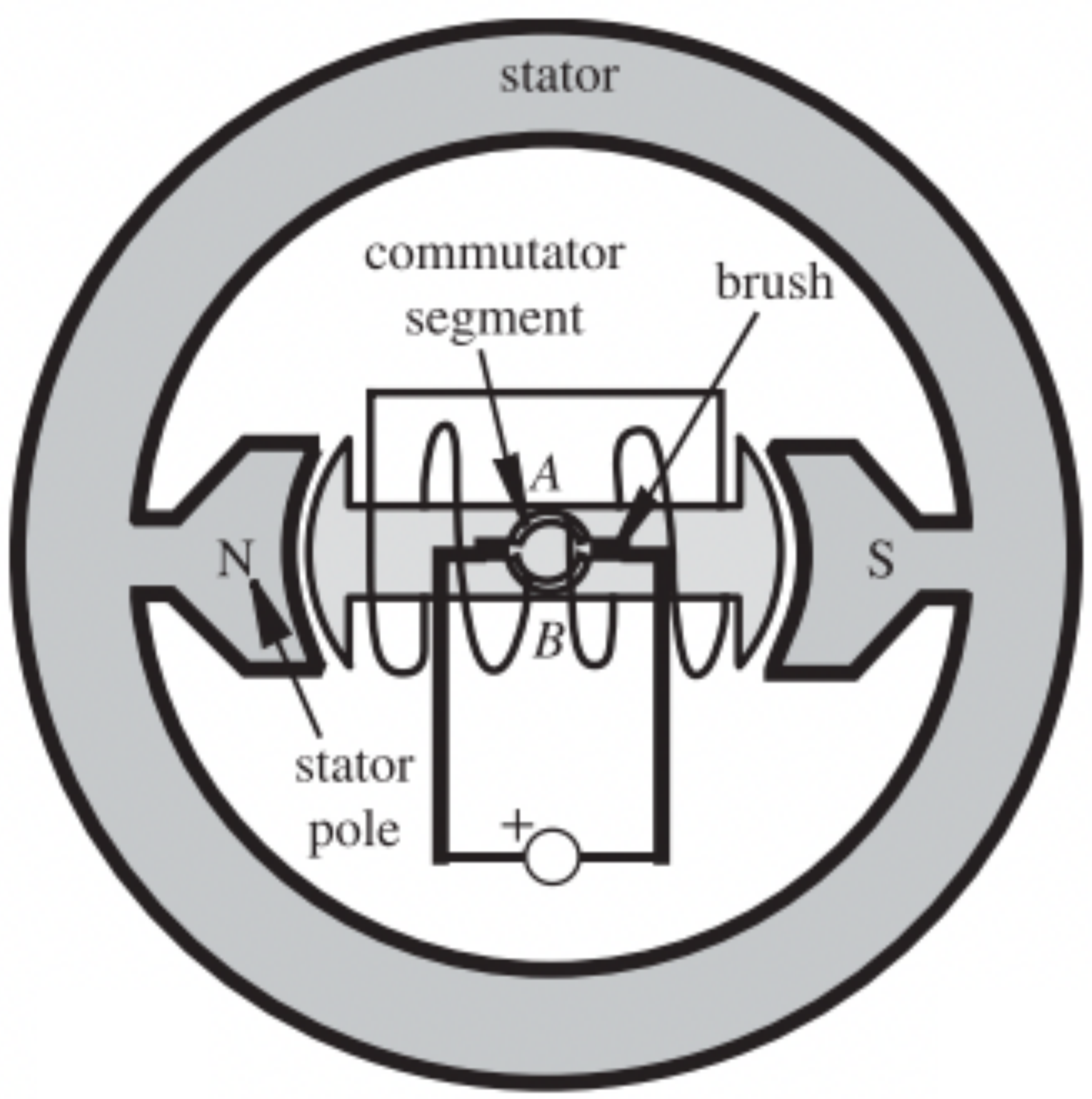


> stator poles - permanent magnets

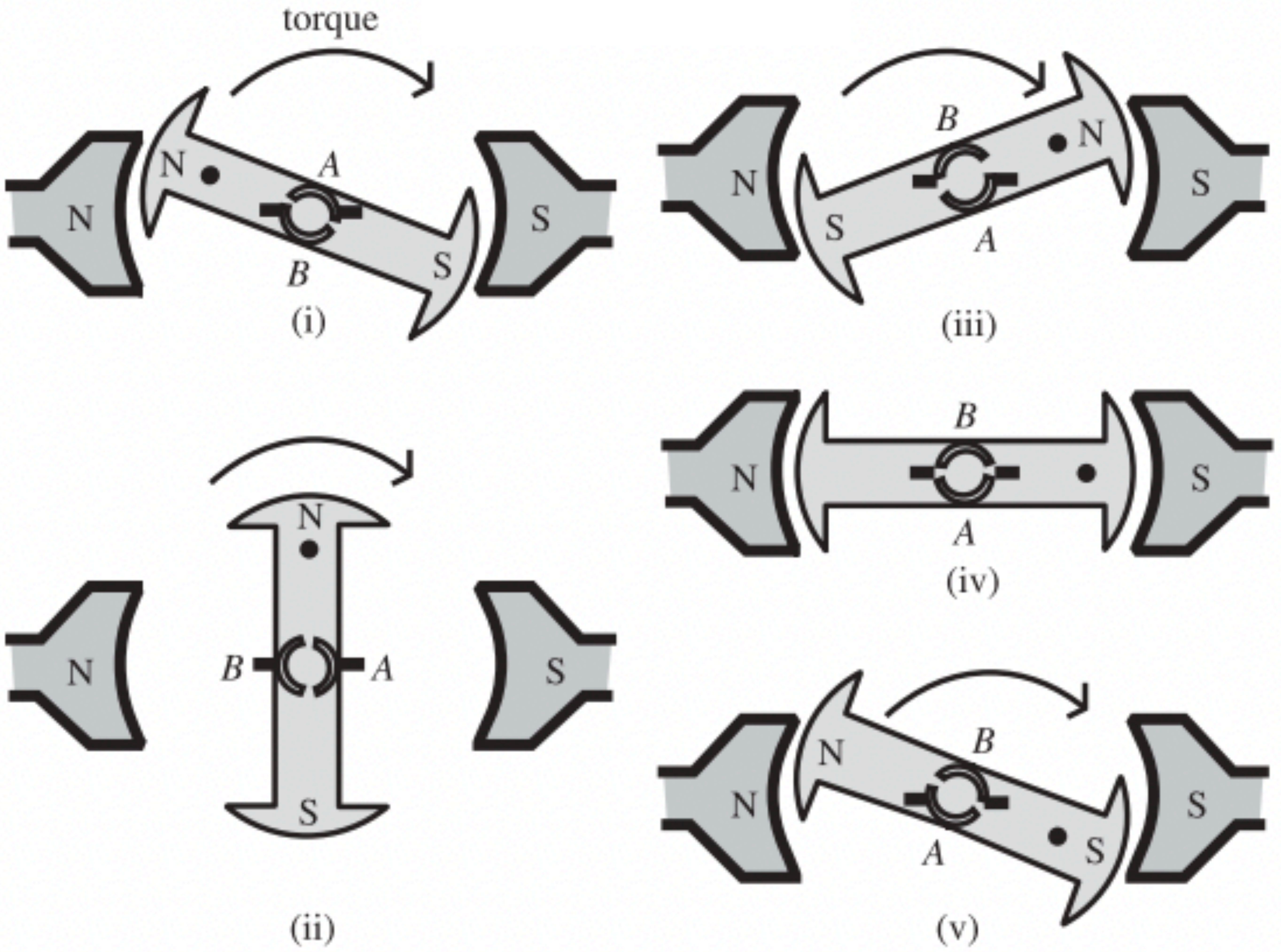
> winding in rotor commutate so the the direction of the magnetic is same of the stator

DC Motors: Working Principle - stator/rotor magnetic fields

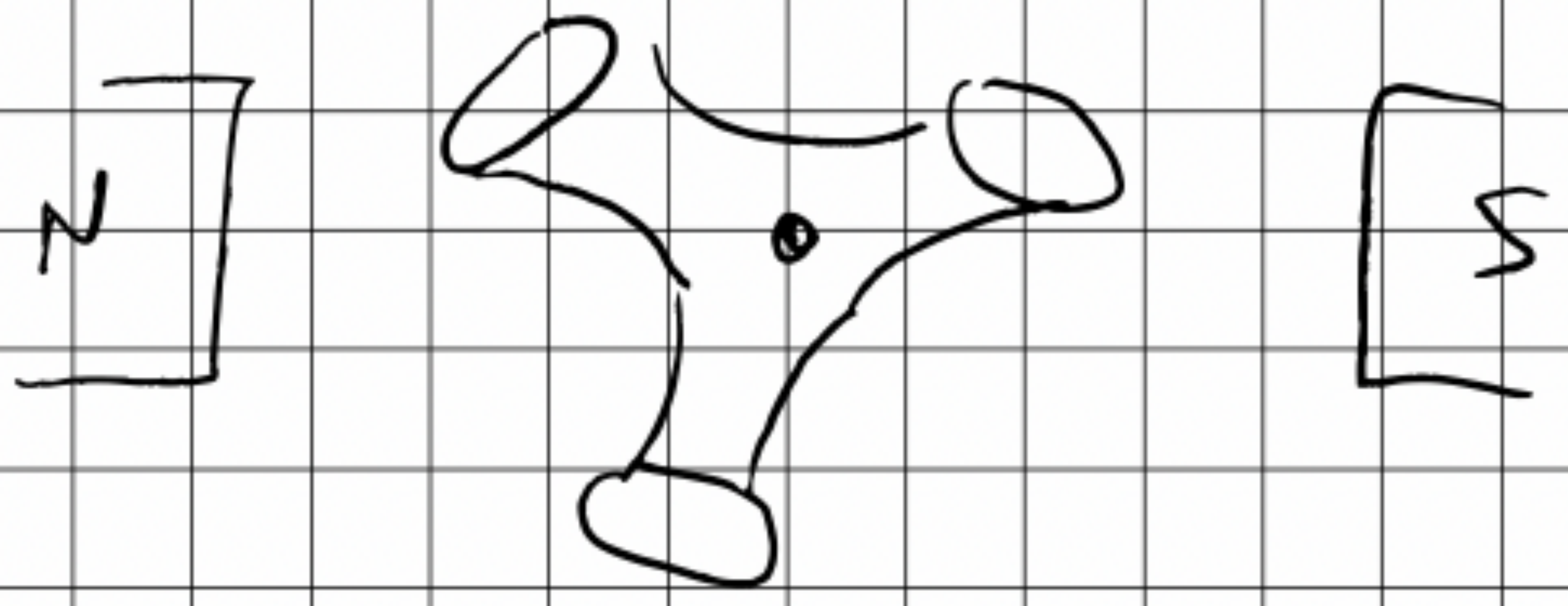
The torque is produced by the fact that like field poles attract and unlike poles repel.



Two Pole
Brushed DC motor



DC Motors: You can have many poles!



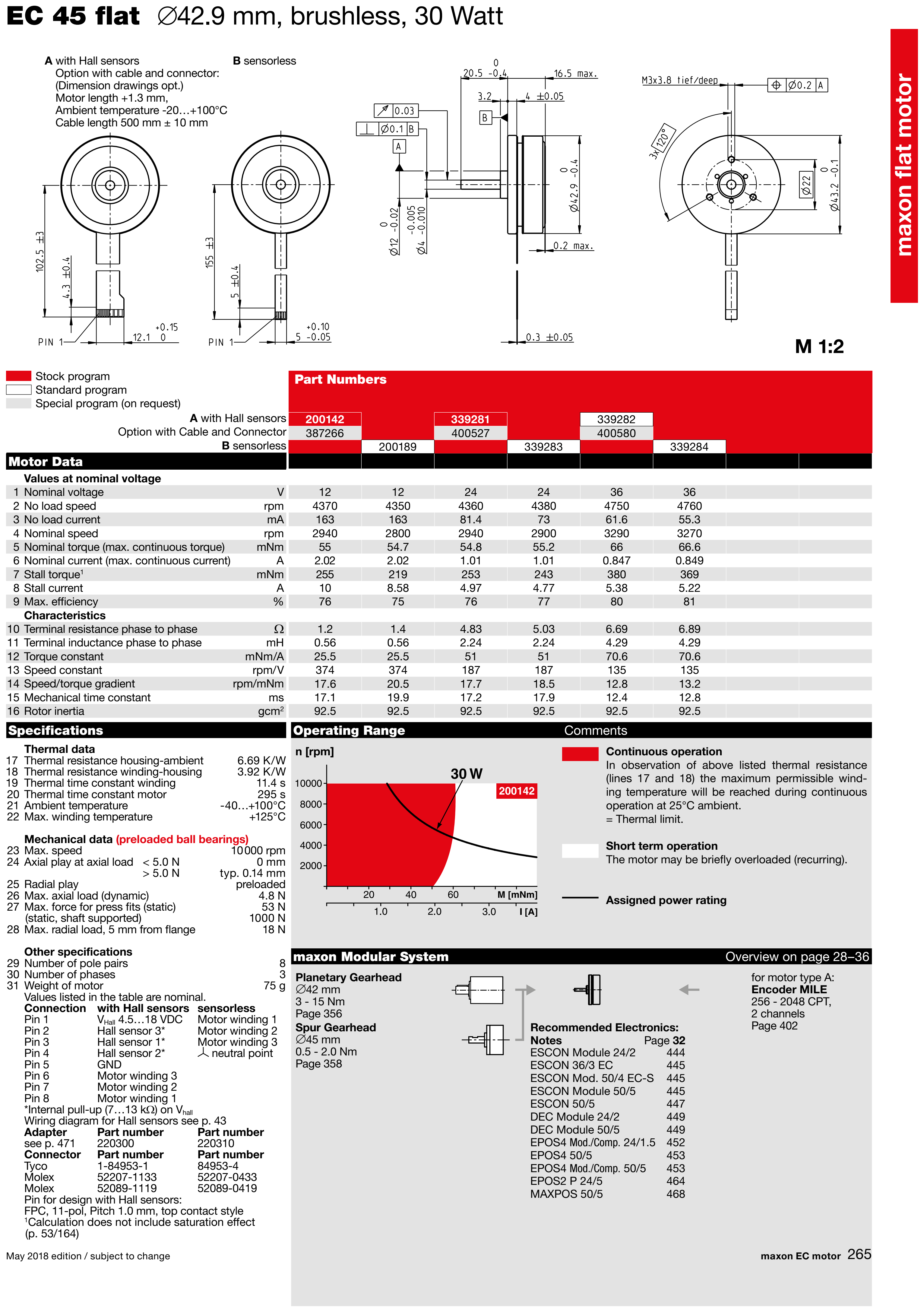
three poles

In general :

less poles : less torque / more speed

more poles : more torque / less speed

$\underbrace{\text{more poles}}\longrightarrow$ "smooth" torque signal



EC 45 flat ∅42.9 mm, brushless, 30 Watt

maxon flat motor

A with Hall sensors
Option with cable and connector:
(Dimension drawings opt.)
Motor length +1.3 mm,
Ambient temperature -20…+100°C
Cable length 500 mm ± 10 mm

B sensorless

M 1:2

🟥 Stock program
☐ Standard program
▨ Special program (on request)

Part Numbers						
A with Hall sensors	200142		339281		339282	
Option with Cable and Connector	387266		400527		400580	
B sensorless		200189		339283		339284

Motor Data

Values at nominal voltage							
1 Nominal voltage	V	12	12	24	24	36	36
2 No load speed	rpm	4370	4350	4360	4380	4750	4760
3 No load current	mA	163	163	81.4	73	61.6	55.3
4 Nominal speed	rpm	2940	2800	2940	2900	3290	3270
5 Nominal torque (max. continuous torque)	mNm	55	54.7	54.8	55.2	66	66.6
6 Nominal current (max. continuous current)	A	2.02	2.02	1.01	1.01	0.847	0.849
7 Stall torque[1]	mNm	255	219	253	243	380	369
8 Stall current	A	10	8.58	4.97	4.77	5.38	5.22
9 Max. efficiency	%	76	75	76	77	80	81
Characteristics							
10 Terminal resistance phase to phase	Ω	1.2	1.4	4.83	5.03	6.69	6.89
11 Terminal inductance phase to phase	mH	0.56	0.56	2.24	2.24	4.29	4.29
12 Torque constant	mNm/A	25.5	25.5	51	51	70.6	70.6
13 Speed constant	rpm/V	374	374	187	187	135	135
14 Speed/torque gradient	rpm/mNm	17.6	20.5	17.7	18.5	12.8	13.2
15 Mechanical time constant	ms	17.1	19.9	17.2	17.9	12.4	12.8
16 Rotor inertia	gcm^2	92.5	92.5	92.5	92.5	92.5	92.5

Specifications

Thermal data	
17 Thermal resistance housing-ambient	6.69 K/W
18 Thermal resistance winding-housing	3.92 K/W
19 Thermal time constant winding	11.4 s
20 Thermal time constant motor	295 s
21 Ambient temperature	-40…+100°C
22 Max. winding temperature	+125°C
Mechanical data (preloaded ball bearings)	
23 Max. speed	10000 rpm
24 Axial play at axial load < 5.0 N	0 mm
> 5.0 N	typ. 0.14 mm
25 Radial play	preloaded
26 Max. axial load (dynamic)	4.8 N
27 Max. force for press fits (static)	53 N
(static, shaft supported)	1000 N
28 Max. radial load, 5 mm from flange	18 N
Other specifications	
29 Number of pole pairs	8
30 Number of phases	3
31 Weight of motor	75 g

Values listed in the table are nominal.

Connection	**with Hall sensors**	**sensorless**
Pin 1	V_{Hall} 4.5…18 VDC	Motor winding 1
Pin 2	Hall sensor 3*	Motor winding 2
Pin 3	Hall sensor 1*	Motor winding 3
Pin 4	Hall sensor 2*	⅄ neutral point
Pin 5	GND	
Pin 6	Motor winding 3	
Pin 7	Motor winding 2	
Pin 8	Motor winding 1	

*Internal pull-up (7…13 kΩ) on V_{hall}
Wiring diagram for Hall sensors see p. 43

Adapter	**Part number**	**Part number**
see p. 471	220300	220310
Connector	**Part number**	**Part number**
Tyco	1-84953-1	84953-4
Molex	52207-1133	52207-0433
Molex	52089-1119	52089-0419

Pin for design with Hall sensors:
FPC, 11-pol, Pitch 1.0 mm, top contact style

[1] Calculation does not include saturation effect (p. 53/164)

Operating Range

Comments

🟥 **Continuous operation**
In observation of above listed thermal resistance (lines 17 and 18) the maximum permissible winding temperature will be reached during continuous operation at 25°C ambient.
= Thermal limit.

☐ **Short term operation**
The motor may be briefly overloaded (recurring).

— **Assigned power rating**

maxon Modular System Overview on page 28–36

Planetary Gearhead
∅42 mm
3 - 15 Nm
Page 356

Spur Gearhead
∅45 mm
0.5 - 2.0 Nm
Page 358

for motor type A:
Encoder MILE
256 - 2048 CPT,
2 channels
Page 402

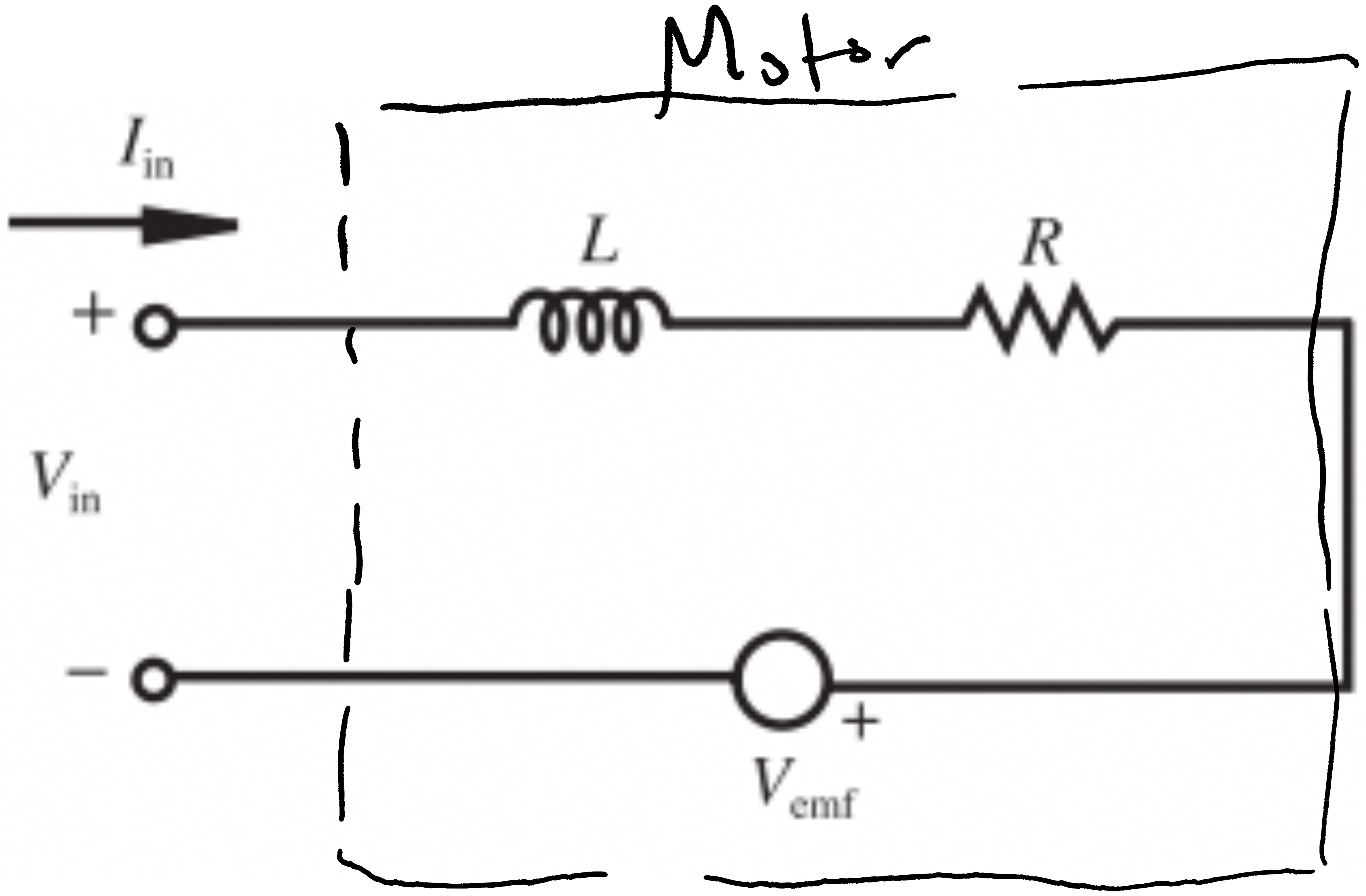
Recommended Electronics:

Notes	Page **32**
ESCON Module 24/2	444
ESCON 36/3 EC	445
ESCON Mod. 50/4 EC-S	445
ESCON Module 50/5	445
ESCON 50/5	447
DEC Module 24/2	449
DEC Module 50/5	449
EPOS4 Mod./Comp. 24/1.5	452
EPOS4 50/5	453
EPOS4 Mod./Comp. 50/5	453
EPOS2 P 24/5	464
MAXPOS 50/5	468

May 2018 edition / subject to change

maxon EC motor 265

Motor Equivalent Circuit



Back EMF Voltage

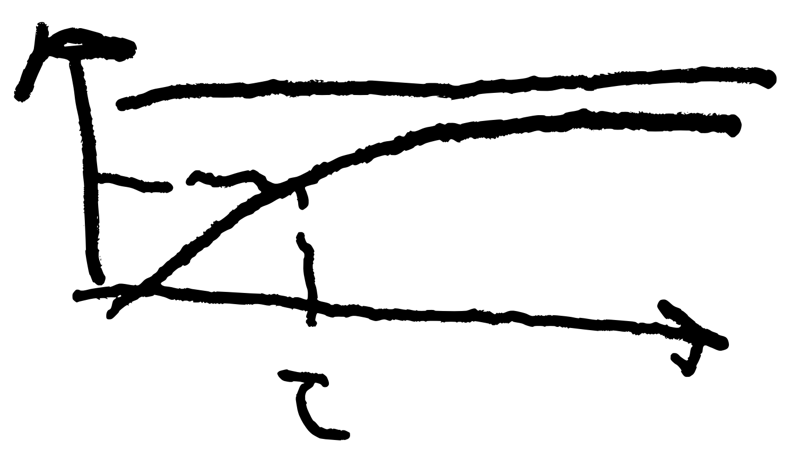
$$V_{emf} = \underbrace{K_e}_{\text{speed constant}} \overbrace{\omega}^{\text{angular velocity}}$$

> the conducting armature rotates in the magnetic produces a voltage (V_{emf}), which oppose V_{in}

$V_L = L\dot{I}_L \qquad V_R = RI_R$

$V_{in} = V_L + V_R + V_{emf} \qquad I_{in} = I_L = I_R$

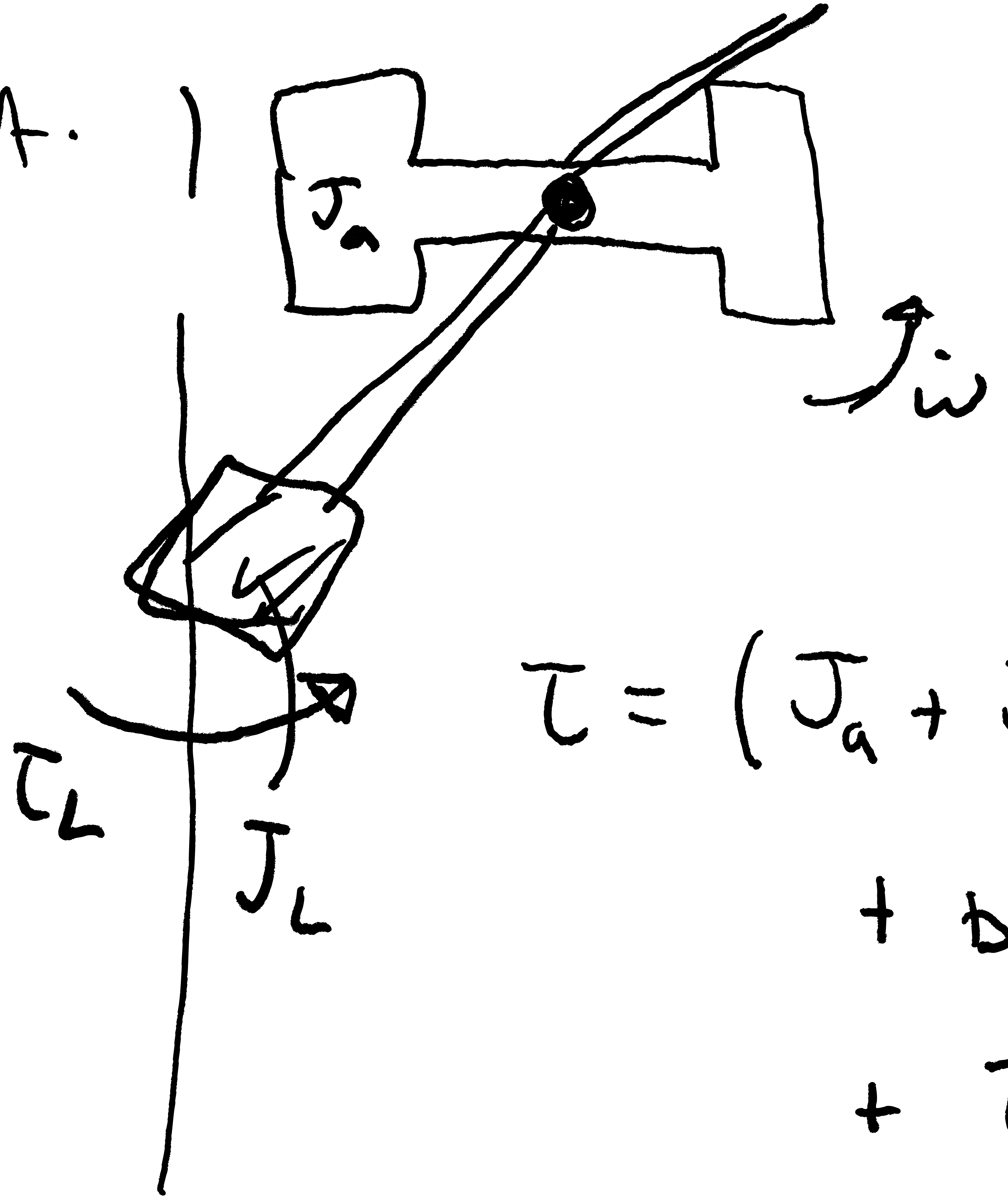
$$\boxed{V_{in} = L\dot{I}_{in} + RI_{in} + K_e\omega}$$



Motor Mechanical Model (permanent magnet DC motor)

Torque ~ current.

$$\tau = K_\tau \cdot I_{in}$$



$$\tau = (J_a + J_L)\dot{\omega} + b\omega^{*} + \tau_L$$

* τ_f = any type of friction model

$$\tau = K_\tau \cdot I_{in}$$

$$\underline{y = mx + b}$$

Steady state response

$$V_{in} = \cancel{L\dot{I}_{in}} + R\,I_{in} + K_e\,\omega$$

$$V_{in} = \left(\frac{R}{K_\tau}\right)\tau + K_e\,\omega$$

$$\therefore \boxed{\tau = \underbrace{\overbrace{\left(\frac{K_\tau}{R}\right)}\,V_{in}}_{C} - \overbrace{\left(\frac{K_e K_\tau}{R}\right)}\,\omega}$$

This Eq. predicts the torque-speed relation for a given input voltage.

$$\tau = \left(\frac{K_\tau}{R}\right) V_{in} - \left(\frac{K_e K_\tau}{R}\right) \omega$$

τ ; T = torque

$$T(\omega) = T_s\left(1 - \frac{\omega}{\omega_{max}}\right)$$

Steady state response

$$T_s = \left(\frac{K_\tau}{R}\right) V_{in}$$

$$\omega_{max} = \frac{T_s R}{K_e K_\tau}$$

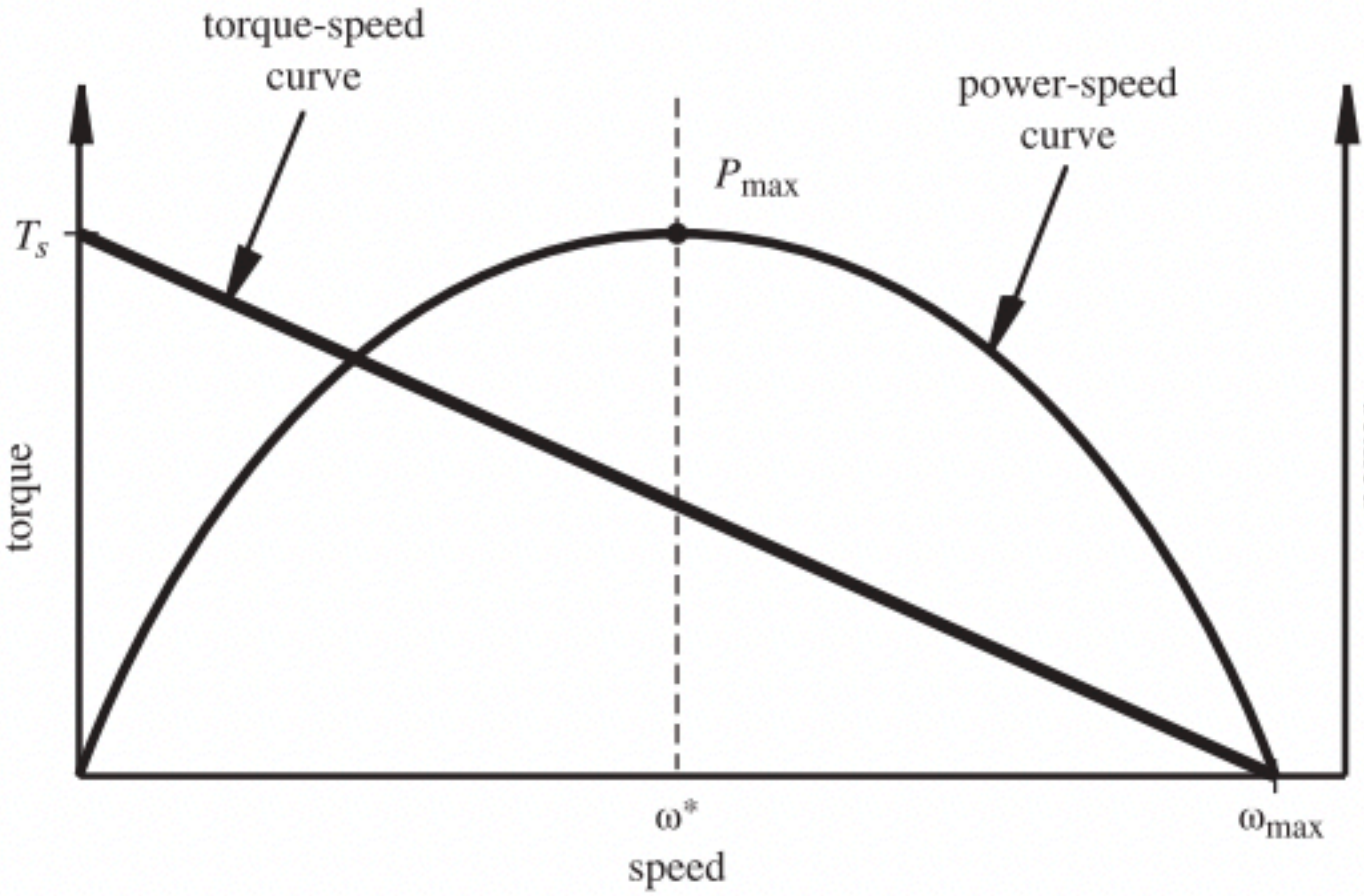


Figure 10.17 Permanent magnet DC motor characteristics.

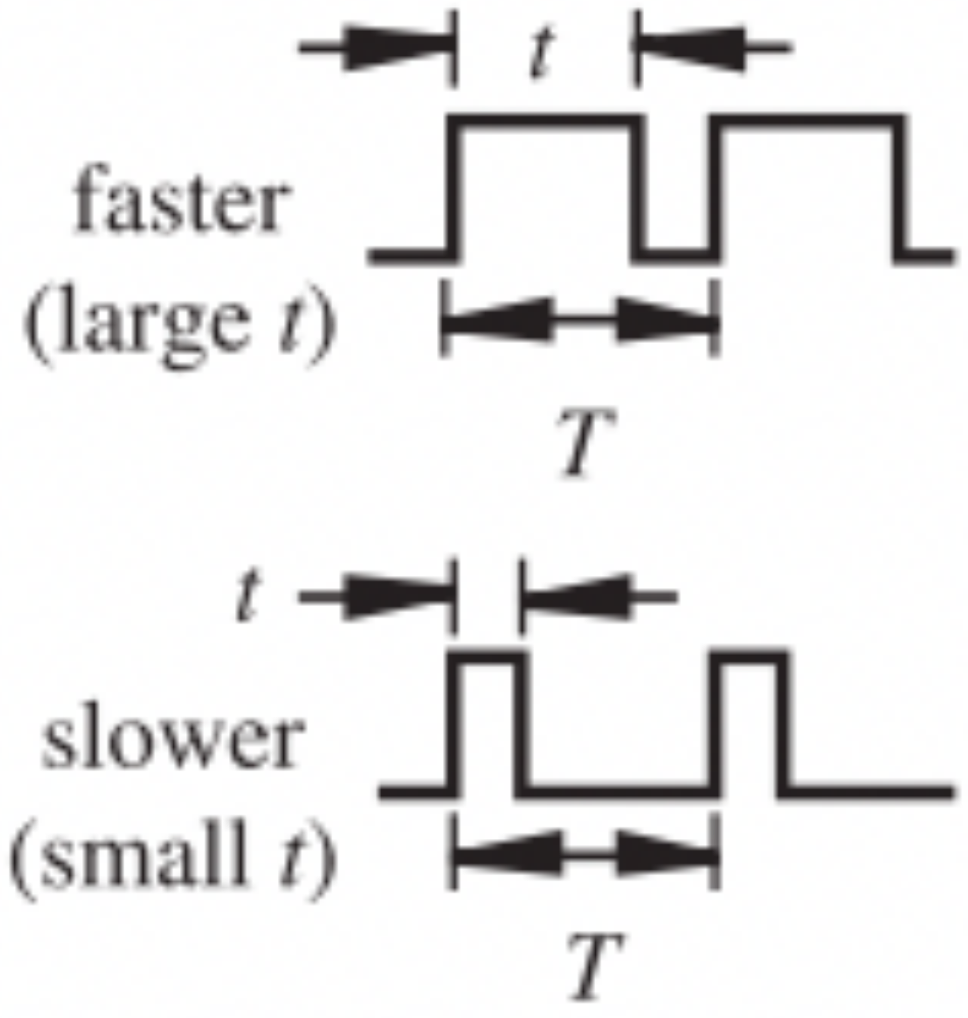
$$P(\omega) = T \cdot \omega = \omega \cdot T_s\left(1 - \frac{\omega}{\omega_{max}}\right)$$

$$\frac{dP}{d\omega} = 0 = T_s\left(1 - \frac{2\omega}{\omega_{max}}\right) = 0$$

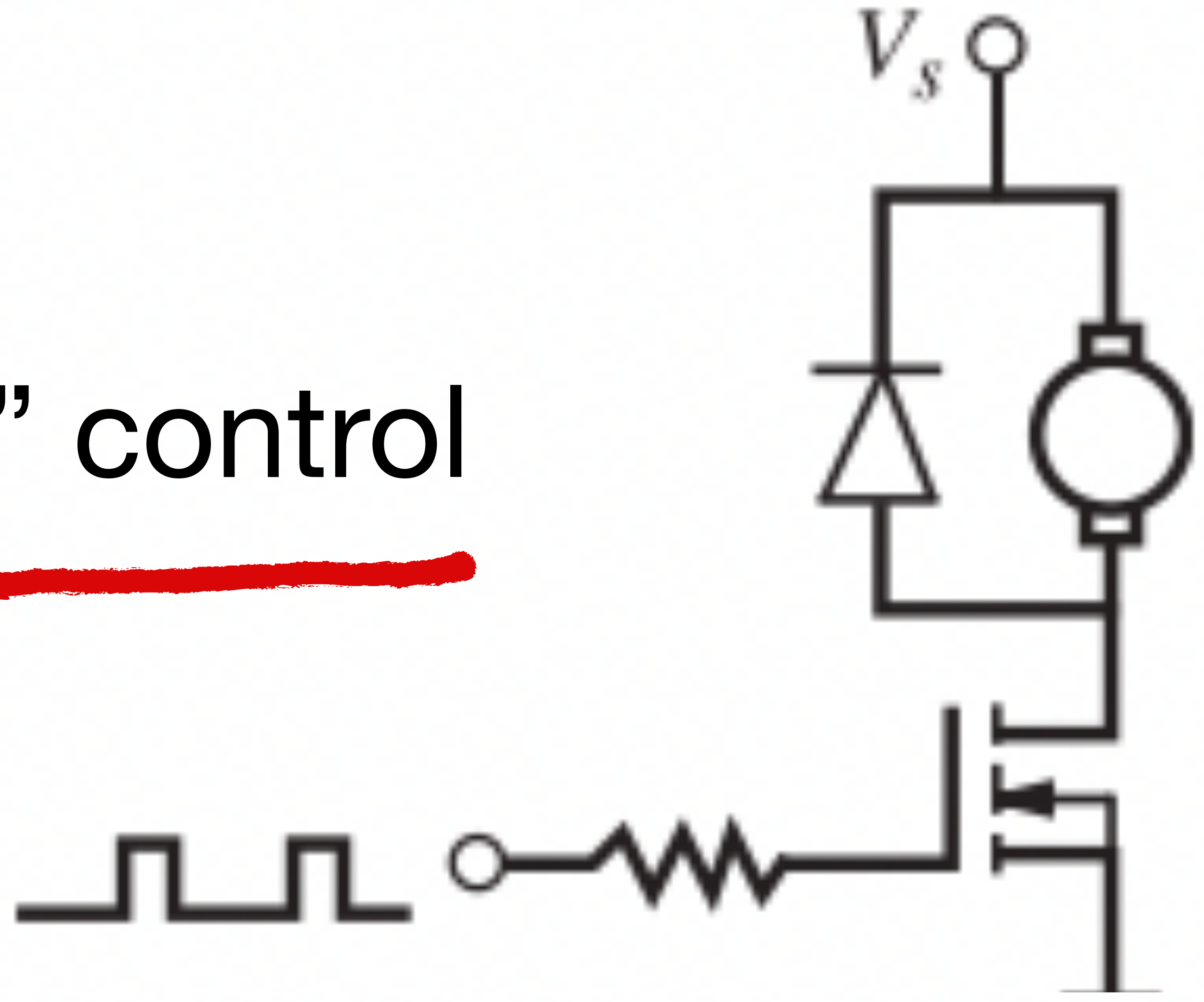
$$\boxed{\omega^* = \frac{1}{2}\omega_{max}}$$

Basic Control

PWM: Pulse Width Modulation

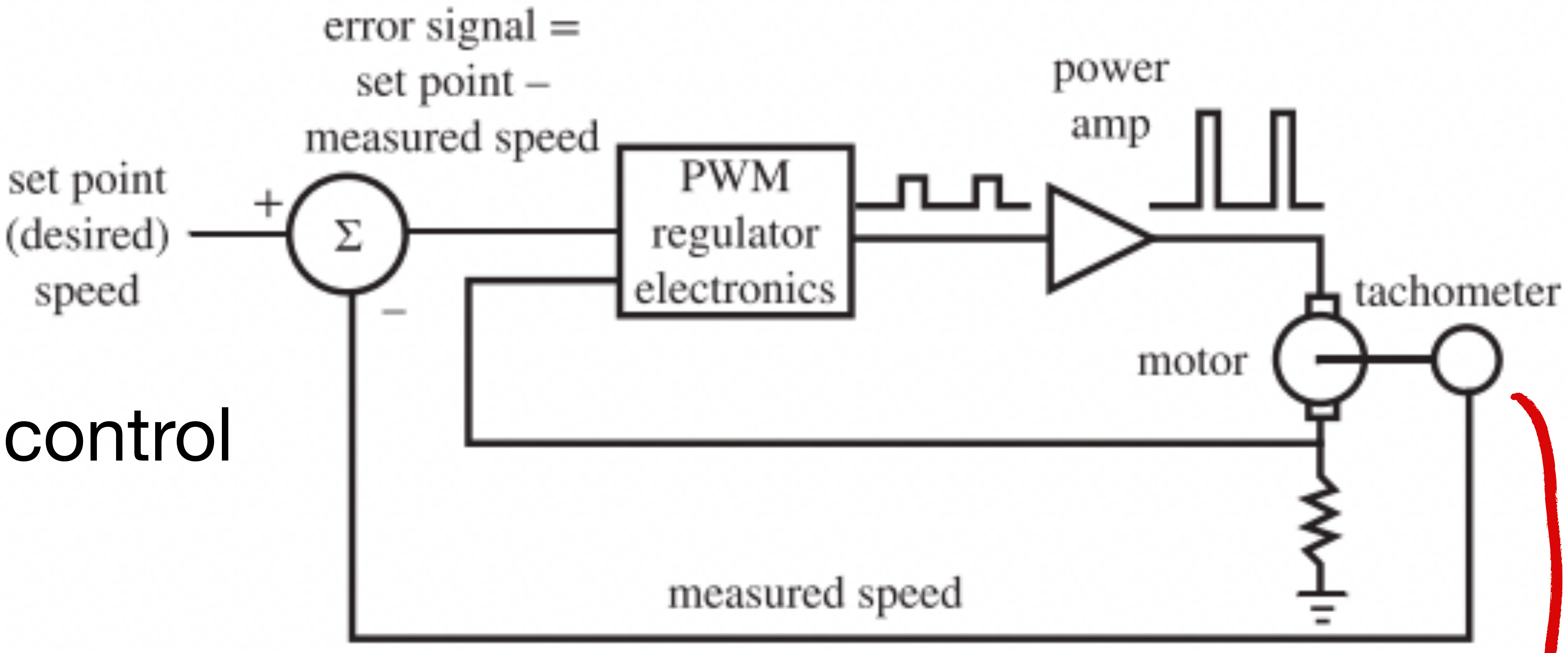


“Open Loop” control



PWM

mosfet



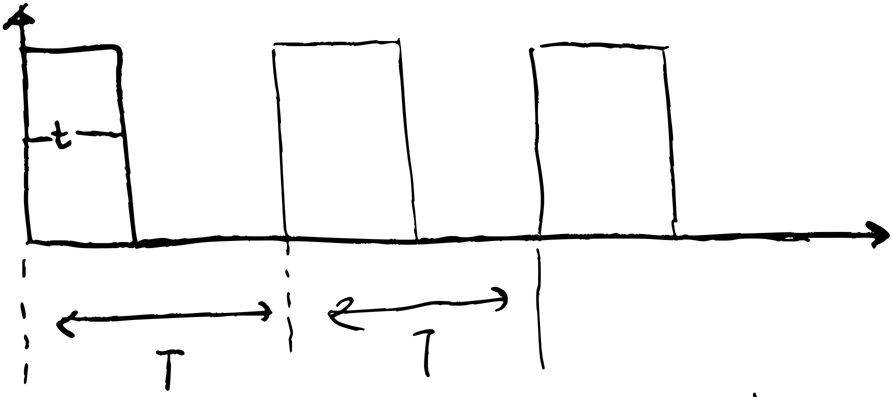
“Closed Loop” speed control

How to go reverse?

Sensor

Speed

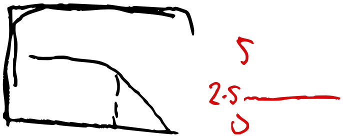
PWM: Pulse width modulation

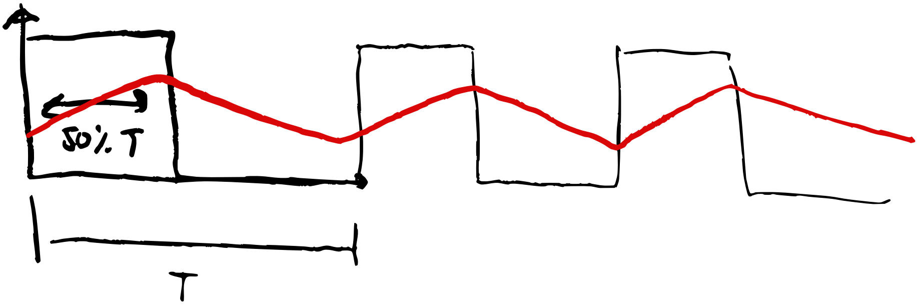


$$f_{pwm} = \frac{1}{T}$$

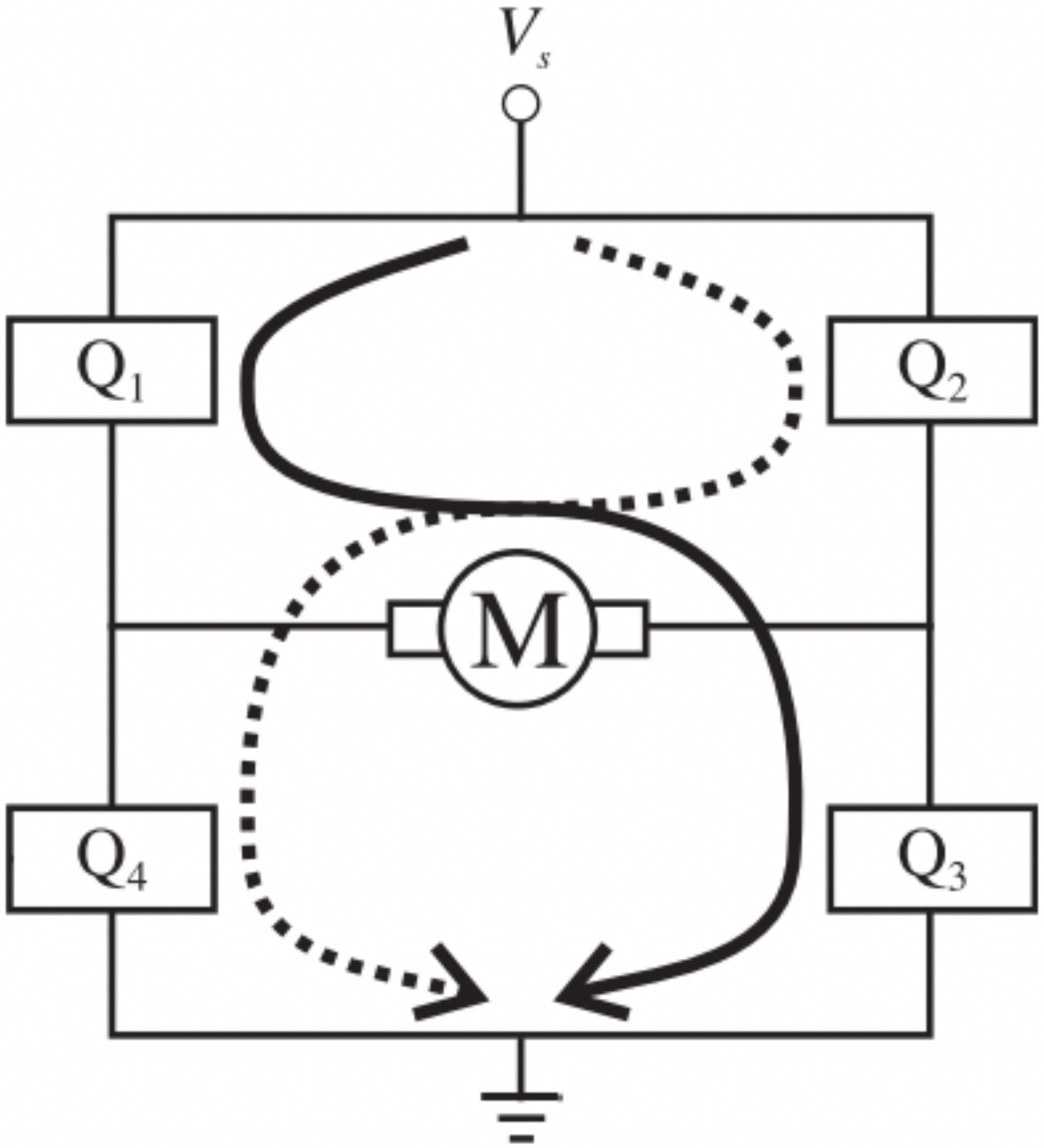
$$\frac{t}{T} = \text{duty cycle}$$

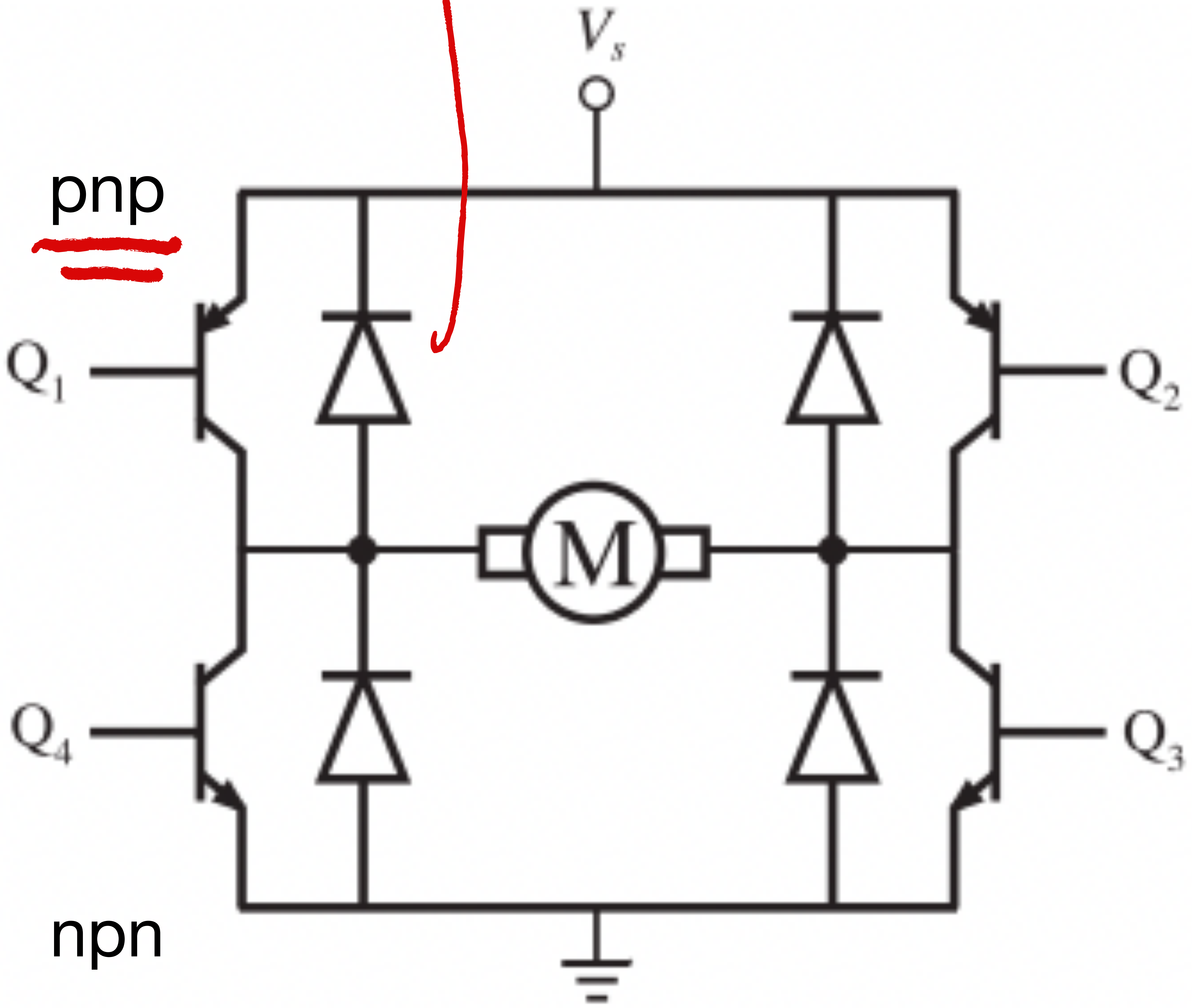
50% duty





H-Bridge motor driver



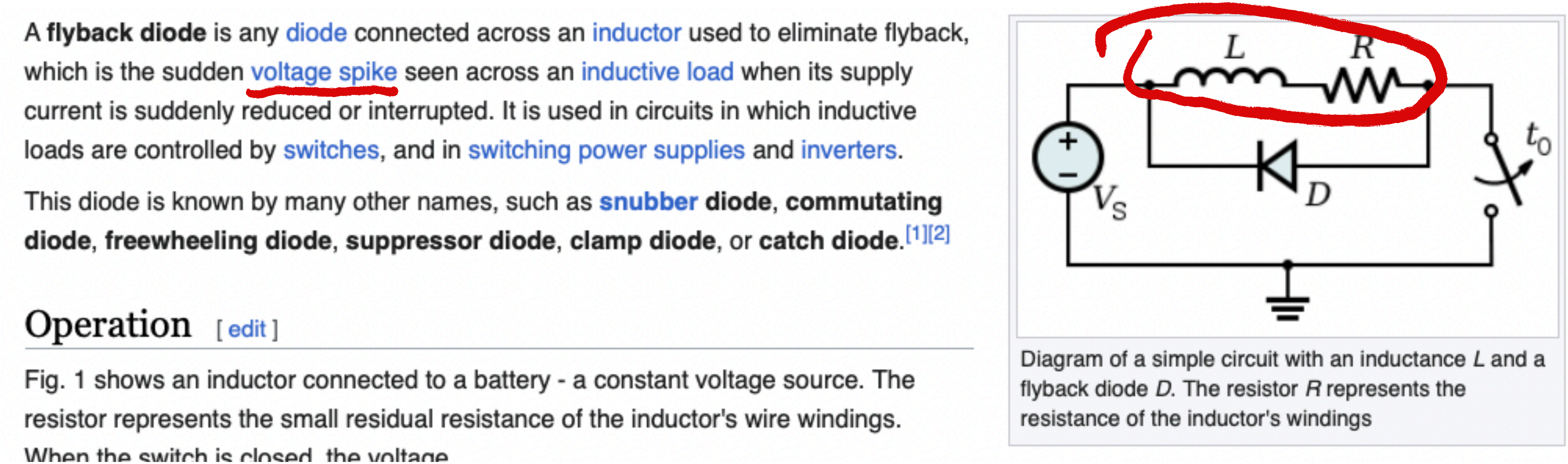


pnp

npn

Fly back diode

Flyback Diode



A **flyback diode** is any diode connected across an inductor used to eliminate flyback, which is the sudden voltage spike seen across an inductive load when its supply current is suddenly reduced or interrupted. It is used in circuits in which inductive loads are controlled by switches, and in switching power supplies and inverters.

This diode is known by many other names, such as **snubber diode**, **commutating diode**, **freewheeling diode**, **suppressor diode**, **clamp diode**, or **catch diode**.[1][2]

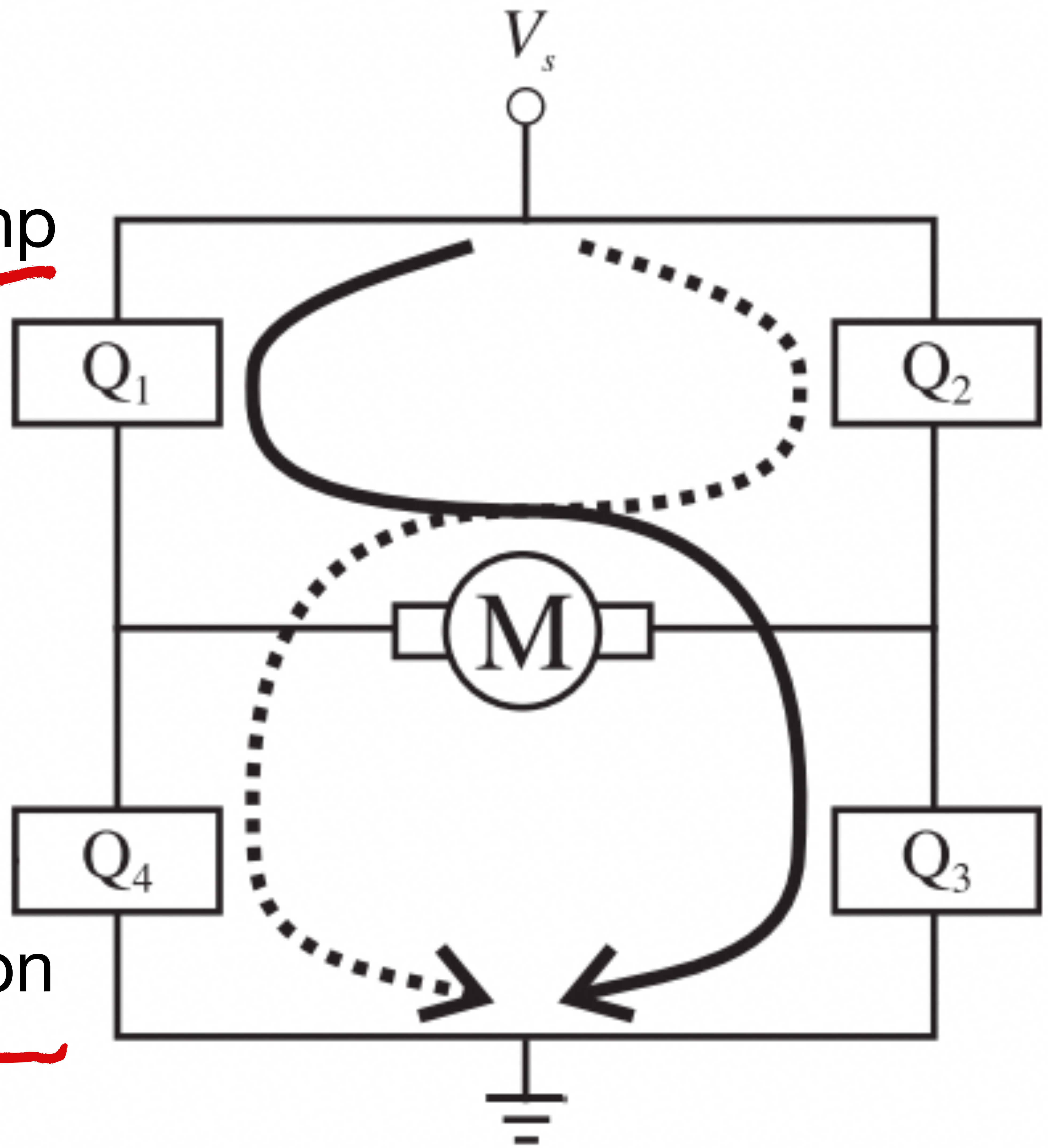
Operation [edit]

Fig. 1 shows an inductor connected to a battery - a constant voltage source. The resistor represents the small residual resistance of the inductor's wire windings. When the switch is closed, the voltage

Diagram of a simple circuit with an inductance *L* and a flyback diode *D*. The resistor *R* represents the resistance of the inductor's windings

H-Bridge motor driver

pnp



npn

Forward motion

Q_1 - Low (ON)

Q_3 - High (ON)

Q_2 - High (OFF)

Q_4 - low (ON)

Stepper Motors

permanent magnet DC motor

- → rotate in both directions
- → precise angular increments
- → sustain holding torque
- → easy to control digitally

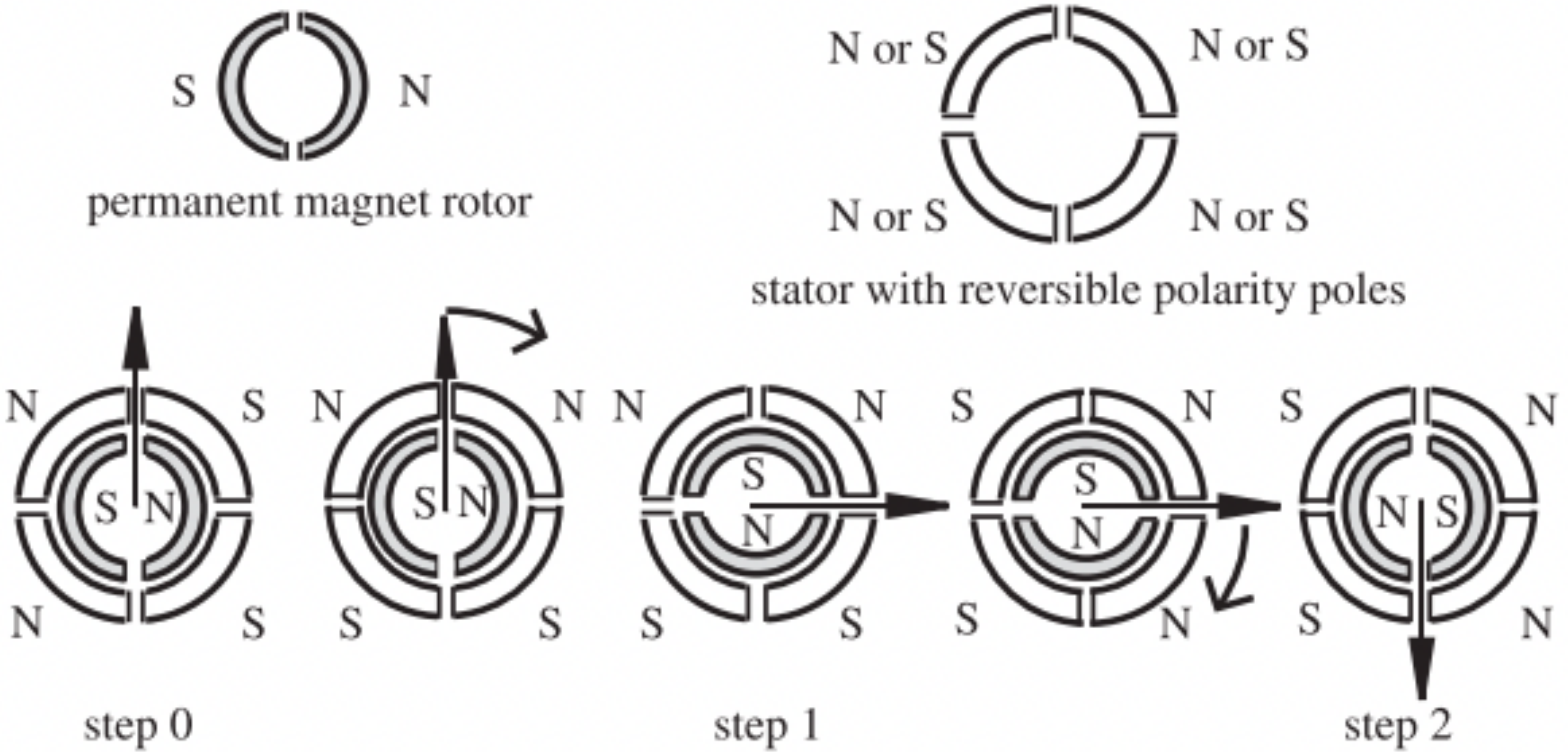
Stepper Motors

Steps:

steps per rev	increments
12	30°
24	15°
72	5°
144	2.5°
180	2°
200	1.8°

micro stepping: 10k steps/rev

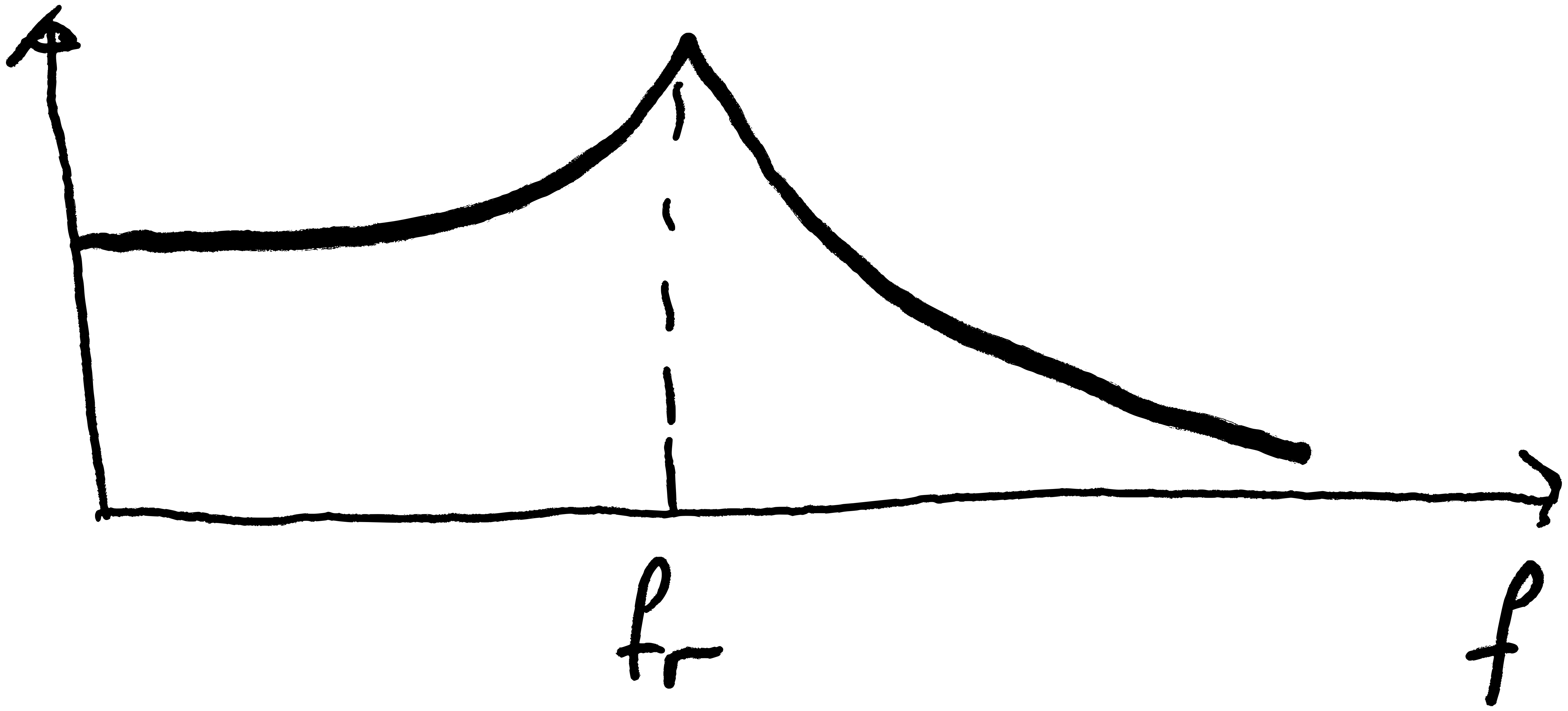
Mechanical Principle of Stepper Motors



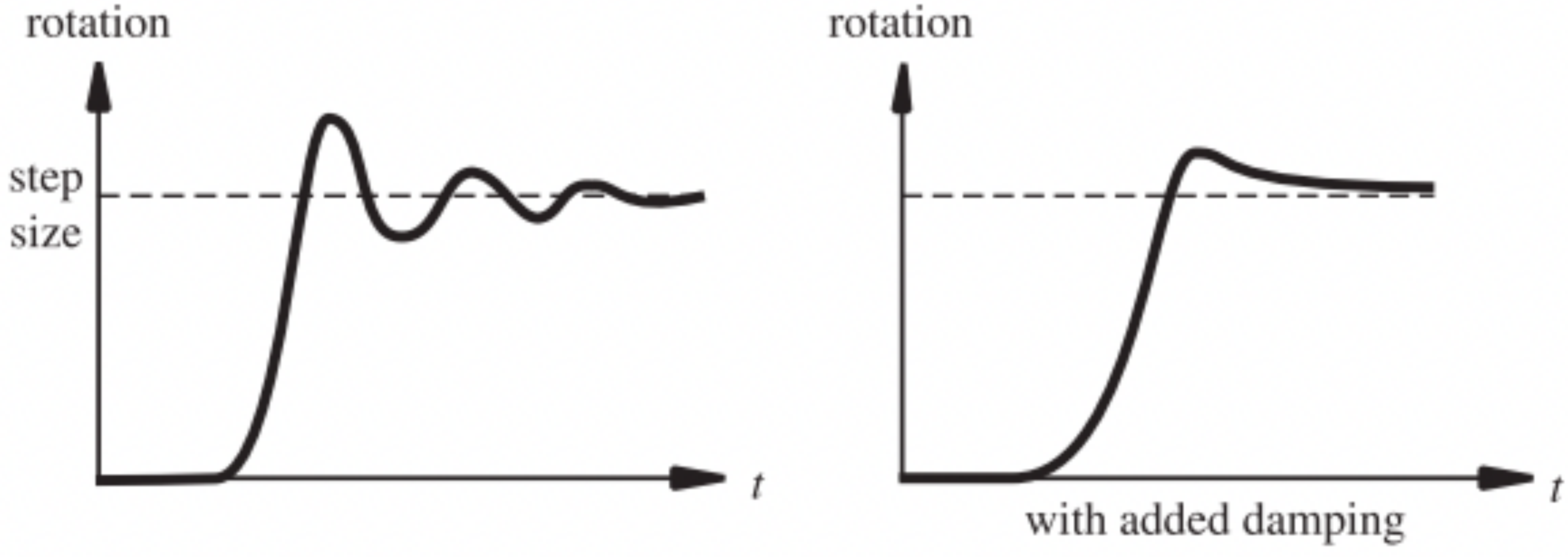
System Response of Stepper Motors

- * high freq. application
  start/stop application
- * possibility of overshoot.

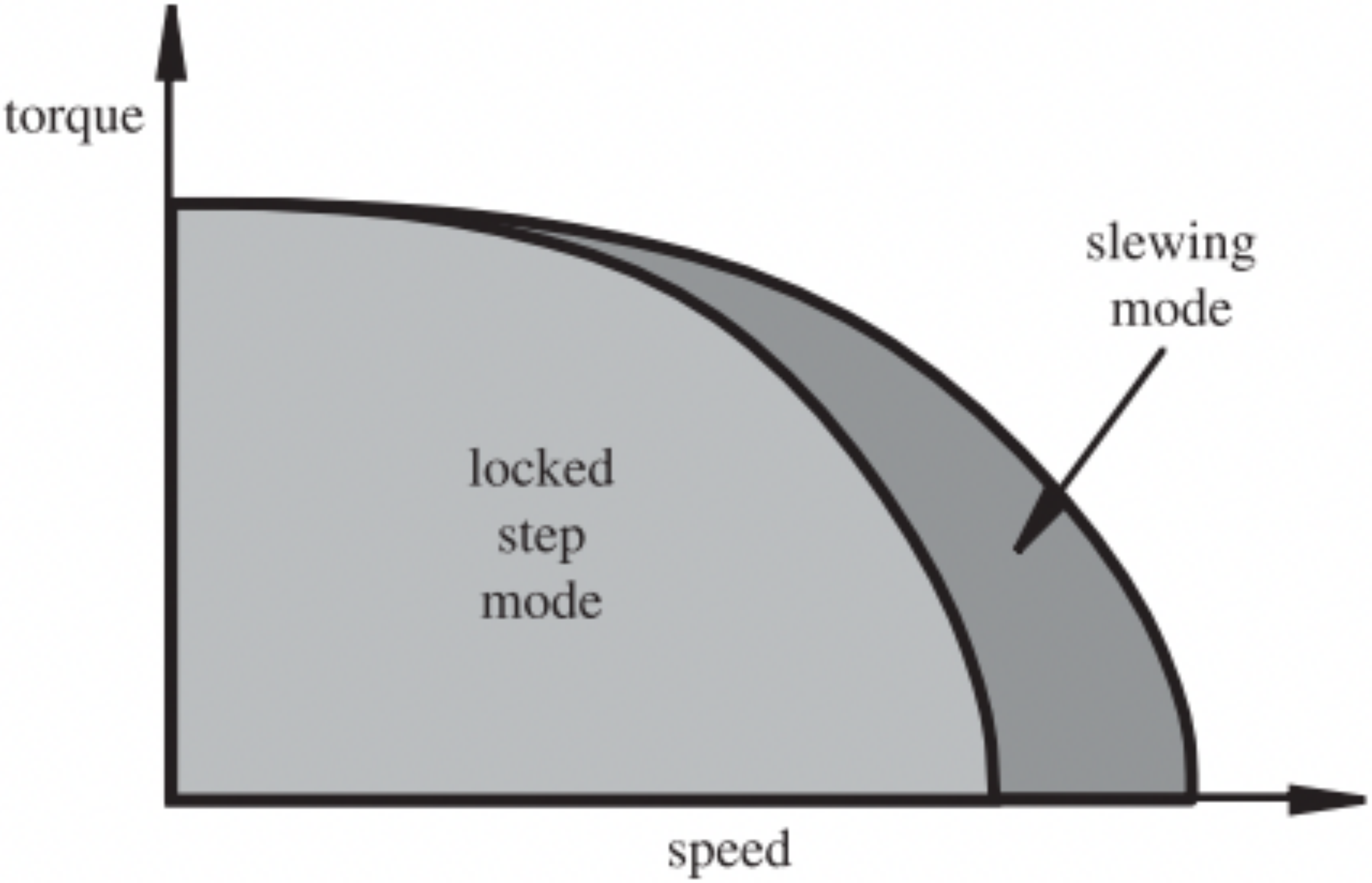
https://www.youtube.com/watch?v=DsYgw3GFHZo



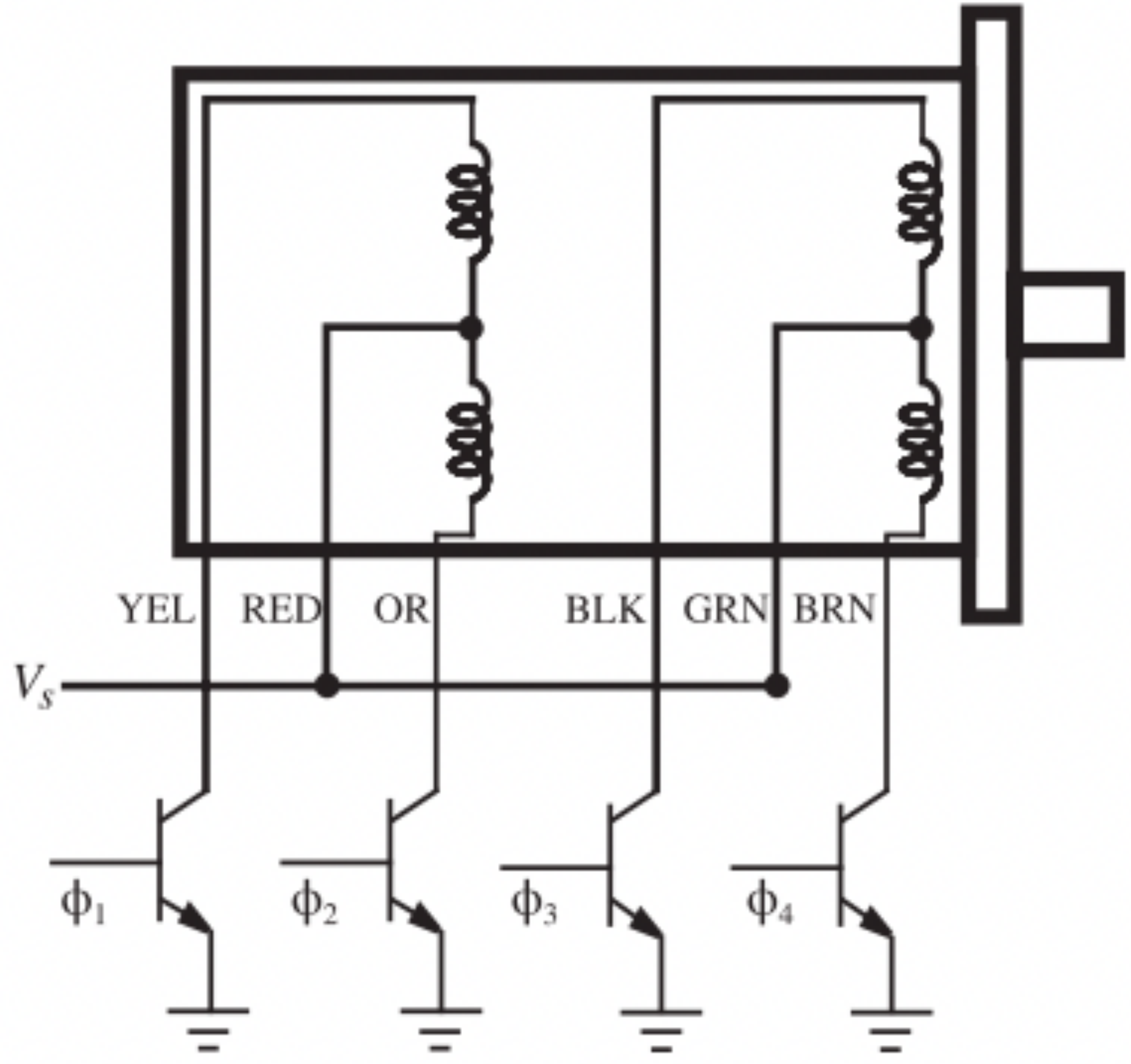
System Response of Stepper Motors

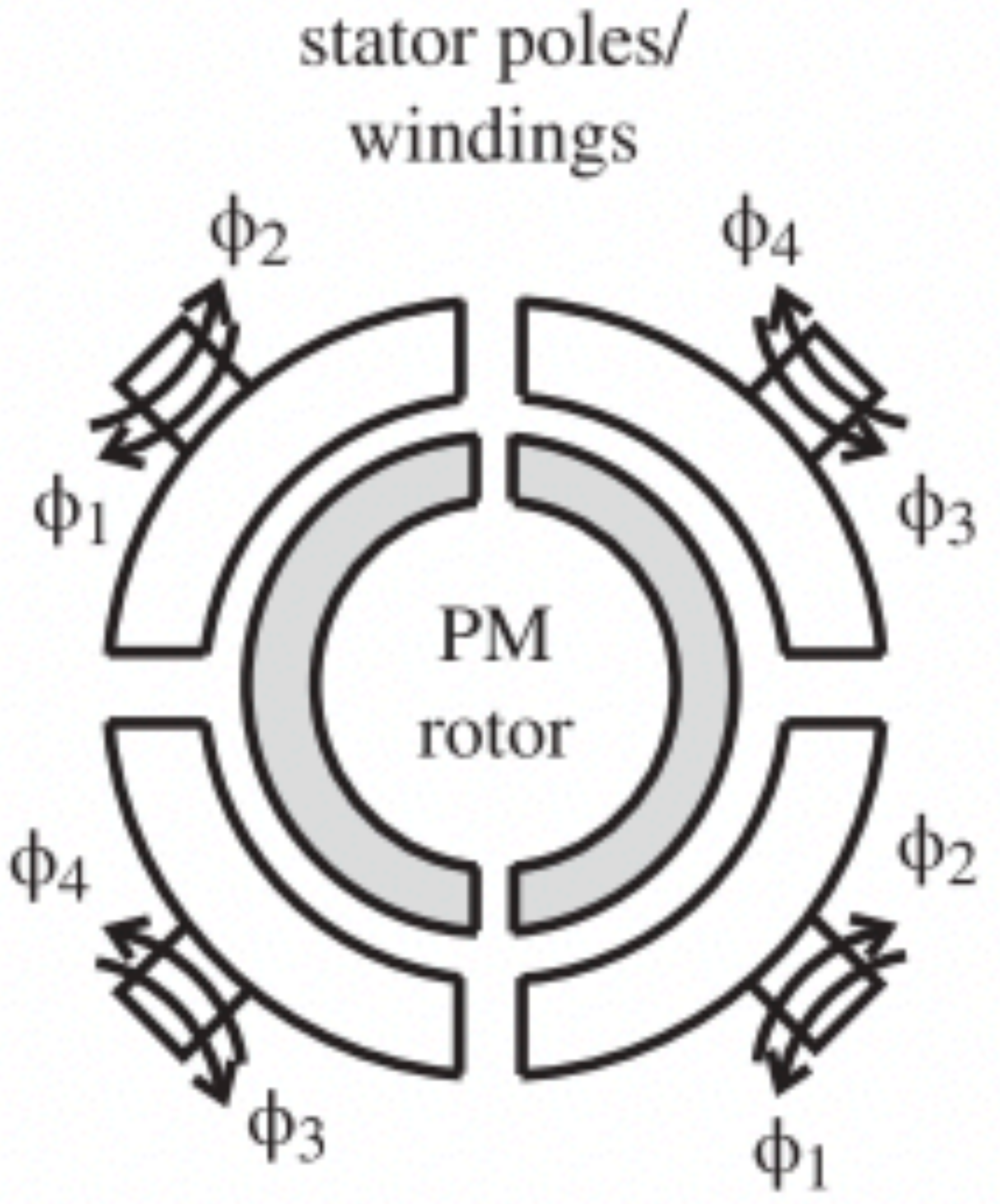


Two possible “speed” regimes for stepper motors



Power Transistors Design and Control
Unipolar (one power supply)





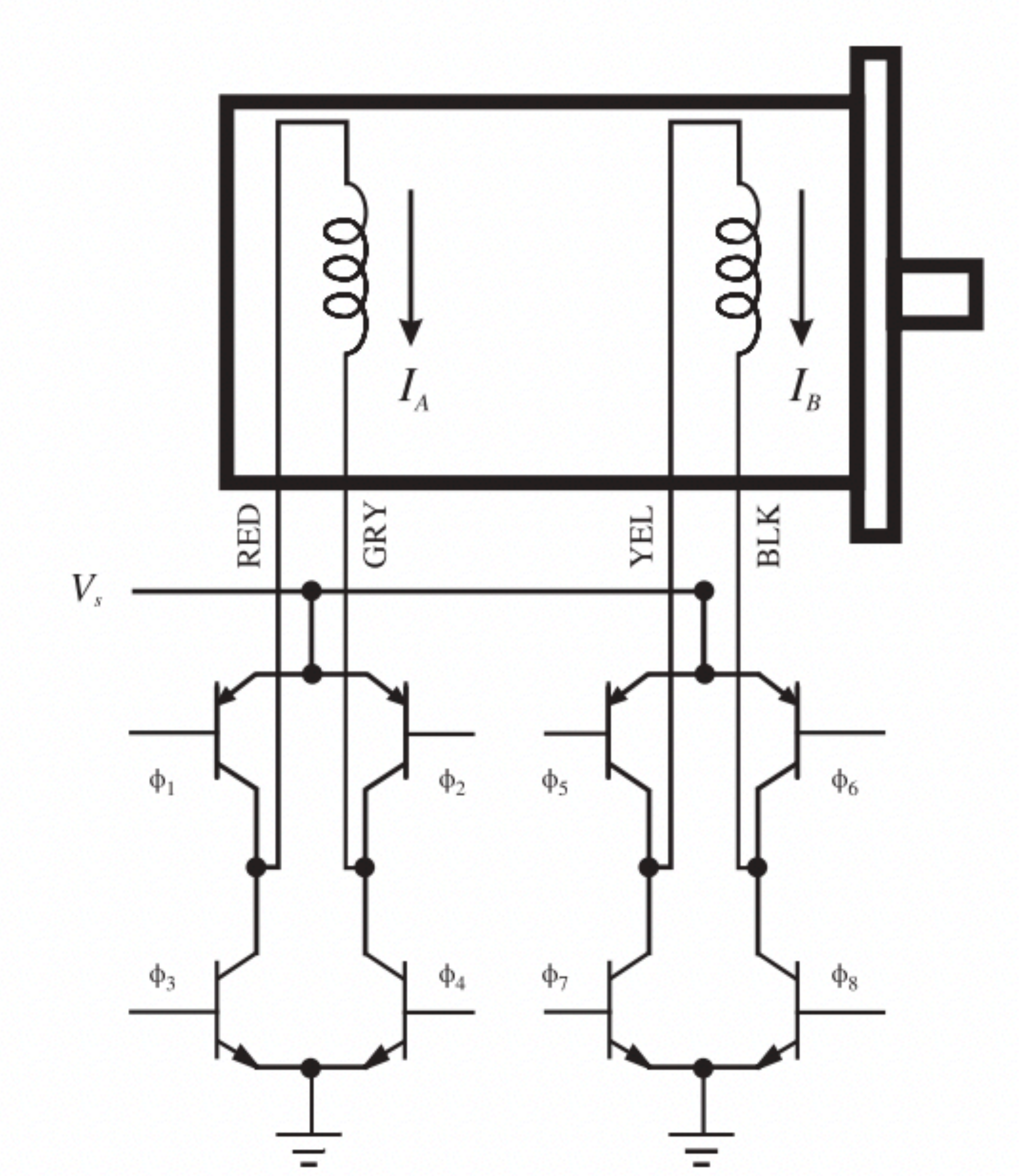
step 1
(ϕ_1, ϕ_3 : ON)

step 1.5
(ϕ_1: ON)

step 2
(ϕ_1, ϕ_4 : ON)

Step	ϕ_1	ϕ_2	ϕ_3	ϕ_4
1	ON	OFF	ON	OFF
2	ON	OFF	OFF	ON
3	OFF	ON	OFF	ON
4	OFF	ON	ON	OFF

Power Transistors Design and Control
Bipolar (switchable power supply)



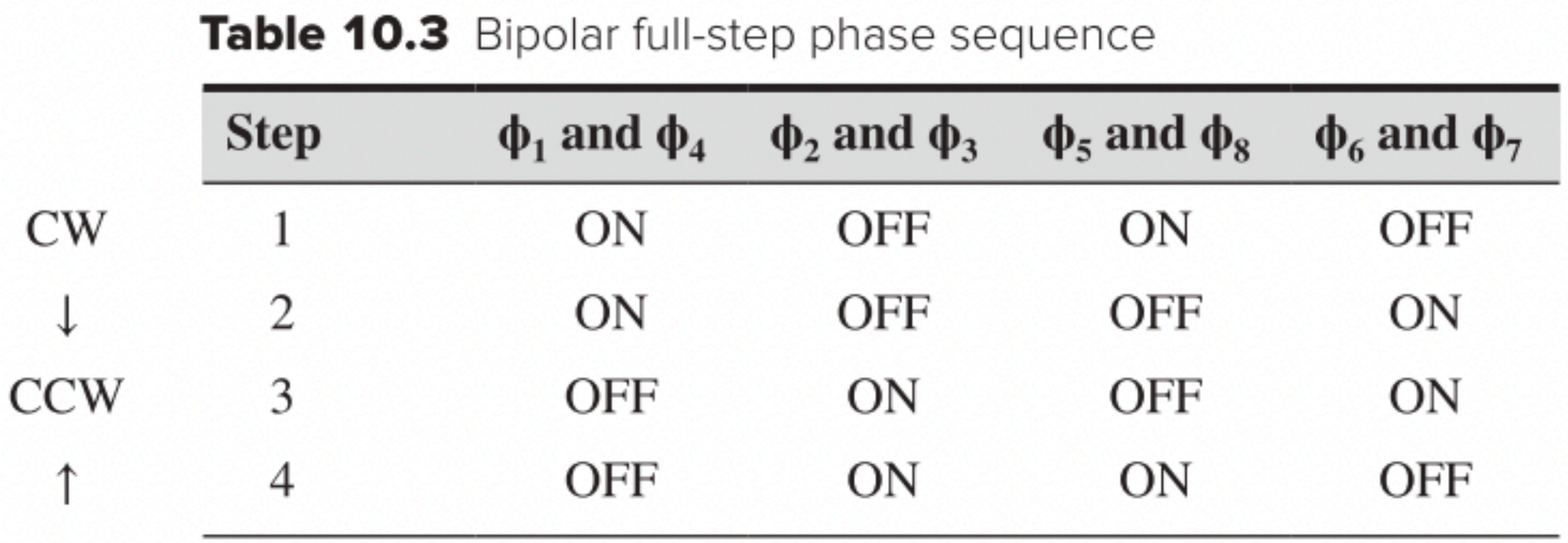
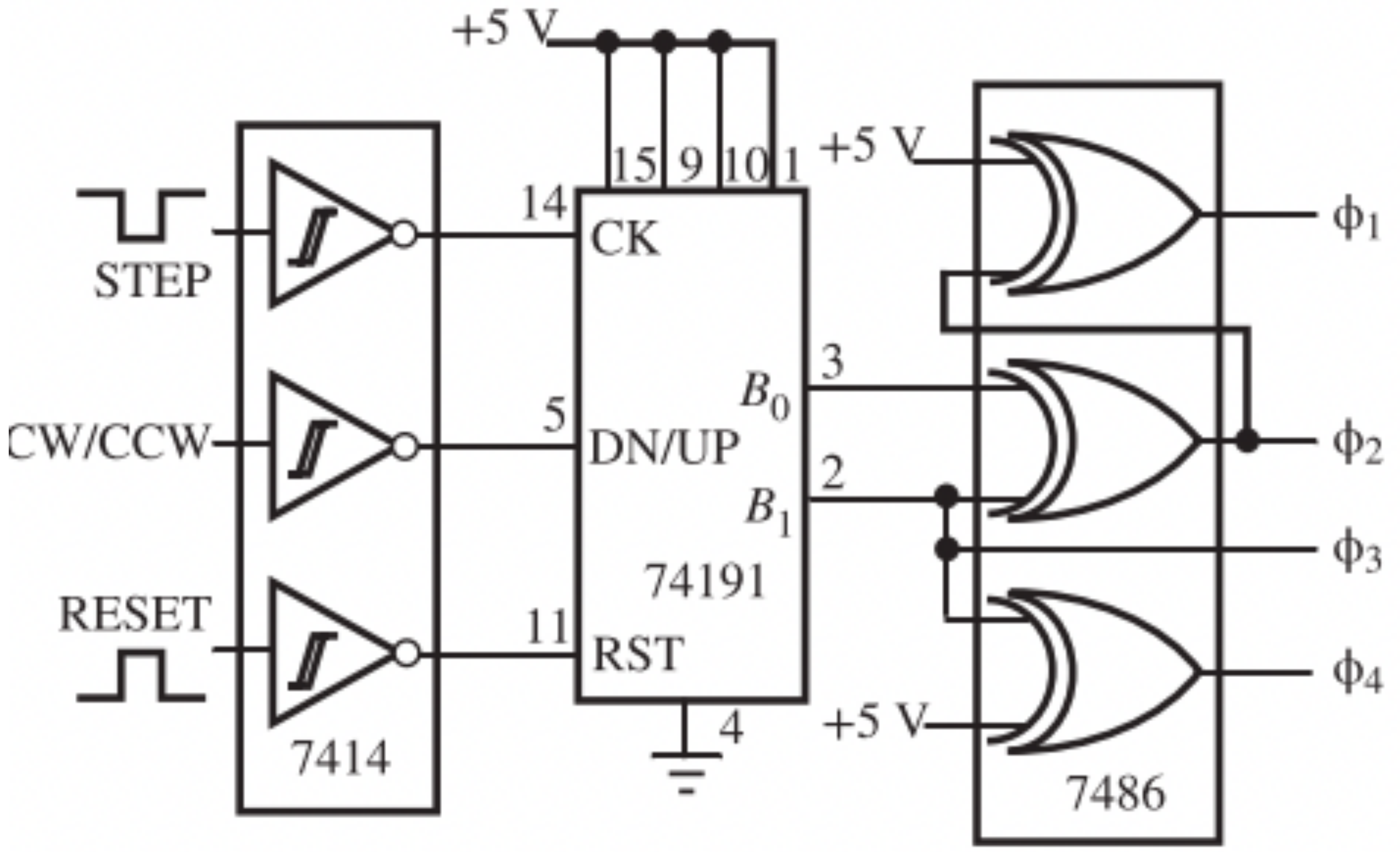


Table 10.3 Bipolar full-step phase sequence

	Step	ϕ_1 and ϕ_4	ϕ_2 and ϕ_3	ϕ_5 and ϕ_8	ϕ_6 and ϕ_7
CW	1	ON	OFF	ON	OFF
↓	2	ON	OFF	OFF	ON
CCW	3	OFF	ON	OFF	ON
↑	4	OFF	ON	ON	OFF

For both bipolar and unipolar, there are drive circuits to take care of phasing



7414 Schmitt trigger buffers, a 74191 up-down counter, and 7486 Exclusive OR gates

Video Links

https://www.youtube.com/watch?v=-qS85aIvleQ&t=289s

https://www.youtube.com/watch?v=DsYgw3GFHZo

https://video-demos.colostate.edu/videos/mechatronics/motors.mp4

https://high-speed-video.colostate.edu/videos/physics/mechatronics/stepper_motor_medium_speed.mp4

https://video-demos.colostate.edu/videos/mechatronics/stepper_motor_design_example.mp4