METE 3100U
Actuators and Power Electronics

Lecture 12
Stepper Motors

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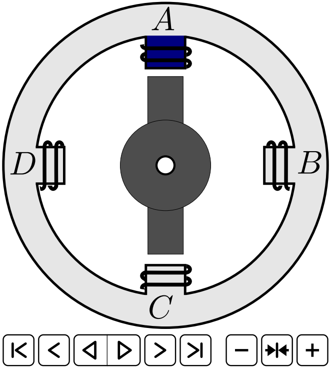
Outline of Lecture 12

By the end of today's lecture, you should be able to

- Understand the working principle of stepper motors
- Analyse and understand different architectures
- Calculate the resolution of a stepper motor

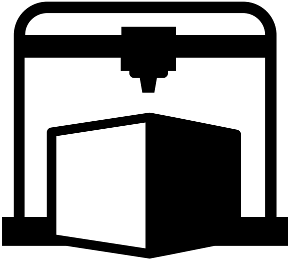
Applications

Stepper motors are widely used for high accuracy positioning systems. What is the working principle of stepper motors?



Applications

Stepper motors are used for precise positioning with a motor, such as hard disk drives, robotics, antennas, and telescopes.

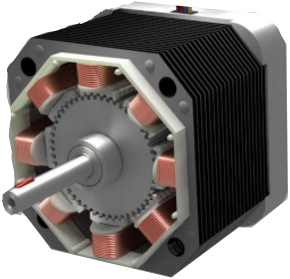


Can stepper motors be used for **high torque** applications?

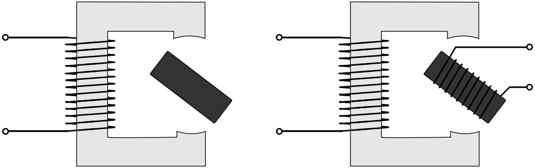
Can stepper motors be used for **high speed** applications?

Applications

As steppers motor are digitally controlled using an input pulse, they are suitable for use with computer controlled systems.



Reluctance motor - from lecture 11



The torque developed in the rotor is

$$T(\theta, i) = \frac{1}{2} i_s^2 \frac{dL_s}{d\theta} + \frac{1}{2} i_r^2 \frac{dL_r}{d\theta} + i_s i_r \frac{dL_m}{d\theta} \tag{1}$$

where

$$L(\theta) = \frac{N^2}{\mathcal{R}(\theta)} \tag{2}$$

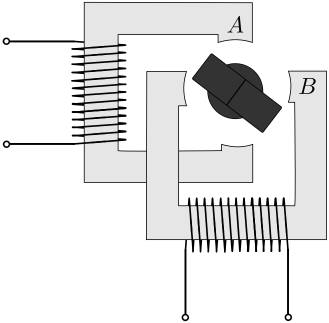
The inductance is a function of the reluctance

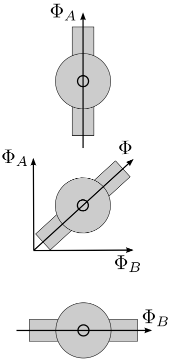
The reluctance is a function of the rotor position

How can we generate continuous rotor rotation?

Stepper motor

Continuous rotation can be created with additional coils





The orientation of the magnetic flux can be controlled.

Types of stepper motor

Stepper motors are synchronous DC motors. They can be classified by

Rotor type

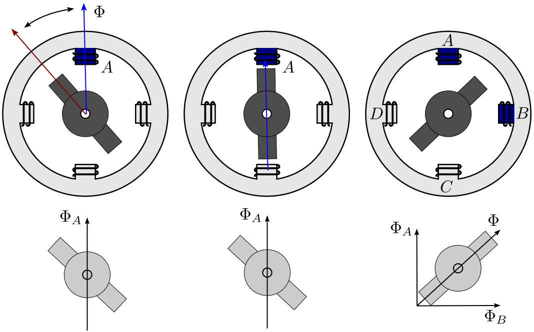
→ Reluctance motors
→ Permanent magnet motors
→ Hybrid motors

Phase wiring

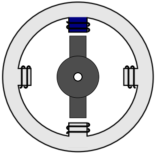
→ Unipolar motor
→ Bipolar motor

Step size control

→ Full step
→ Half step
→ Micro step

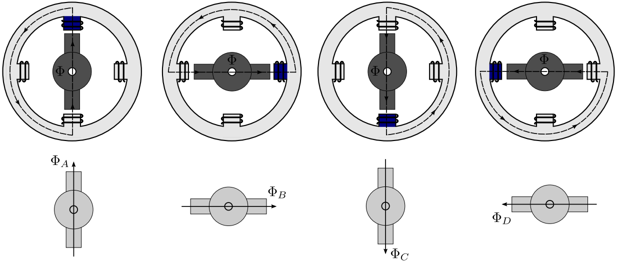


Reluctance motors



4-phase, 2-pole, variable reluctance stepper motor

Full-step, single phase operation

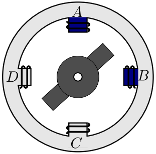


In each step, the rotor moves by $\Delta\theta = \frac{360^\circ}{pN}$

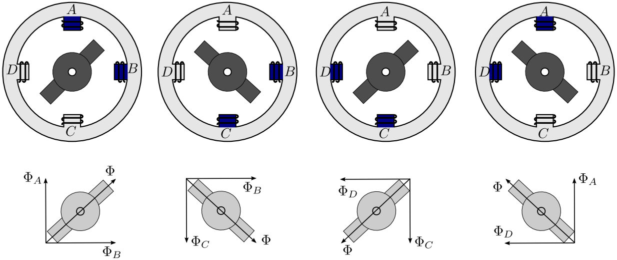
$\Rightarrow$ p is the number of phases ($p = 4$)

$\Rightarrow$ N is the number pole pairs ($N = 1$)

Reluctance motors



Full-step, **double phase** operation

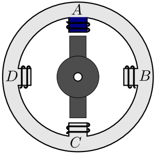


In each step, the rotor moves by $\Delta\theta = \frac{360^\circ}{pN}$

Double phase results in 30-40% more torque than single-phase

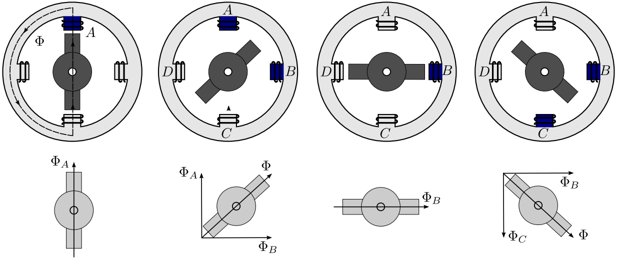
Requires 2 times the power of single-phase mode

Reluctance motors



4-phase, 2-pole, variable reluctance stepper motor

Half-step, single phase operation



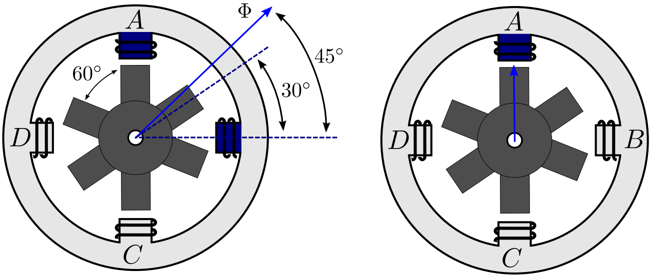
In each step, the rotor moves by $\Delta\theta = \frac{360^\circ}{2pN} = 45^\circ$

Multipole reluctance motor

To reduce the size of the steps:

→ Increase the number of phases: control issues

→ Increase the number of poles



In each step, the rotor moves by $\Delta\theta = \frac{360^{\circ}}{2pN}$

⇒ p is the number of phases ($p = 4$)

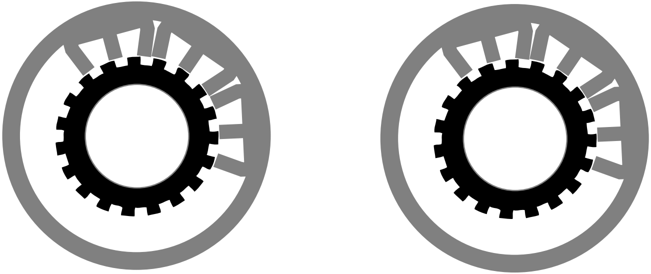
⇒ N is the number of pole pairs ($N = 3$)

Microstep reluctance motor

To reduce the size of the steps:

$\rightarrow$ Increase the number of phases: control issues

$\rightarrow$ Increase the number of poles



In each step, the rotor moves by $\Delta\theta = \frac{360^\circ}{xp}$

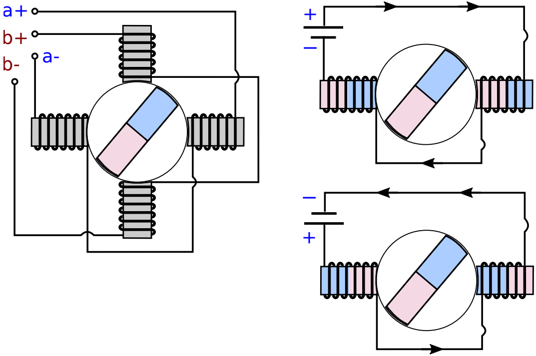
$\Rightarrow$ p is the number of phases ($p = 3$)

$\Rightarrow$ N is the number of rotor teeth ($x = 11$)

Bipolar stepper motor

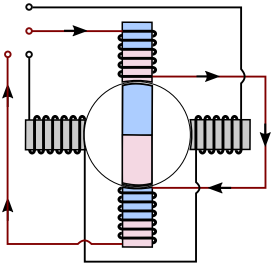
A bipolar stepper motor has one winding per stator phase.

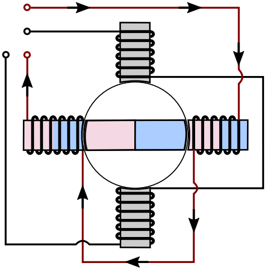
A two phase bipolar stepper motor will have 4 leads ($a+$, $a-$, $b+$, $b-$).



Reversal of current direction through a winding is necessary during operation.

Bipolar stepper motor





	A	B	θ	A	B	θ
Step 1	0	+V	0°	0	+V	0°
Step 2	-V	0	-90°	+V	0	$+90^\circ$
Step 3	0	-V	-180°	0	-V	$+180^\circ$
Step 4	+V	+0	-270°	-V	0	$+270^\circ$

Bipolar stepper motor interfacing

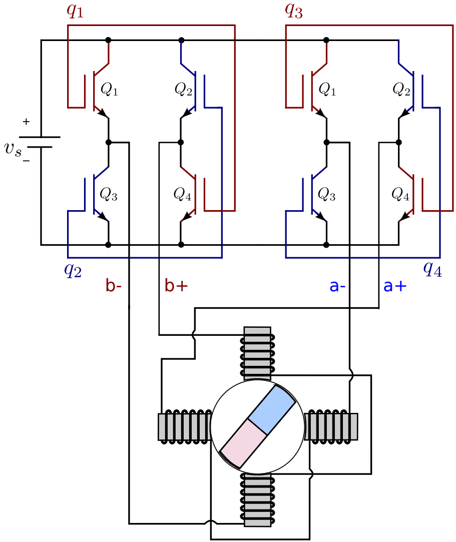
2 H-bridges can be used to power the motor

Voltage in Phase B

q_1	q_2	phase B
0	0	
0	1	
1	0	
1	1	not used

Voltage in phase A

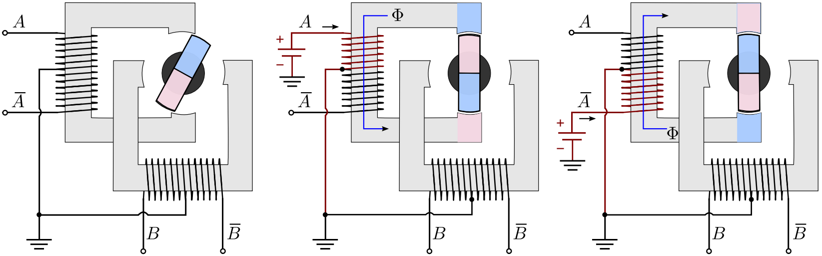
q_3	q_4	phase A
0	0	
0	1	
1	0	
1	1	not used



Unipolar stepper motor

The unipolar motor operates with one winding with a center tap per phase.

A different winding section is switched on for each direction of Φ.



Full-step commutation sequence:

→ Counter-clockwise: $A \rightarrow B \rightarrow \bar{A} \rightarrow \bar{B}$

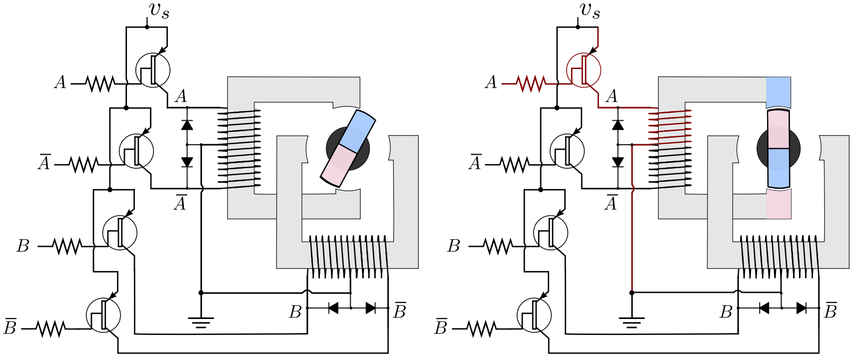
→ Clockwise: $A \rightarrow \bar{B} \rightarrow \bar{A} \rightarrow B$

What happens if A and $\bar{A}$ are activated at the same time?

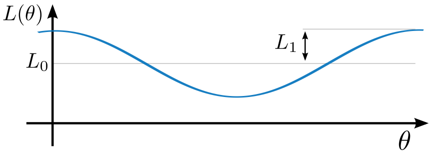
Unipolar stepper motor interfacing

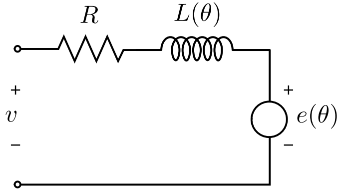
→ The current in a given phase always flows in the same direction

→ 4 Mosfets can be used to power an unipolar motor



Modelling





The winding inductance is

$$L(\theta) = L_0 + L_1 \cos(M\theta) \quad (3)$$

→ M is the number of rotor poles, θ is the rotor position.

The total torque is the sum of the torques produced by the p phases

$$T = \sum_{j=1}^{p} \frac{1}{2} i(t)_j^2 \frac{dL(\theta)_j}{d\theta} \quad (4)$$

with (for one phase)

$$e(\theta) = i \frac{ML_1}{N} \sin(M\theta) \frac{d\theta}{dt} \quad (5)$$

Limitations

The torque due to one phase is

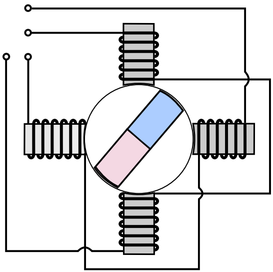
$$T_j(t) = kI_j(t)\sin(\phi - \theta)$$

→ k is a motor constant

→ ϕ gives the orientation of the magnetic flux

→ θ is the rotor position

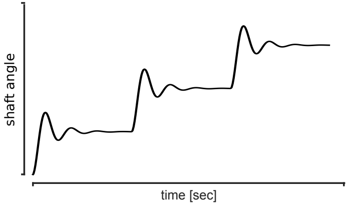
→ $i(t)$ is the winding current



Windings have a high inductance L a time constant τ:

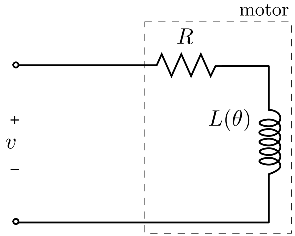
$$\tau = \frac{L}{R}$$

High response time bounds the speed!



Exercise 52

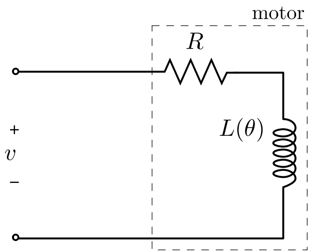
A three-phase reluctance stepper motor has a winding resistance of $R = 1\ \Omega$, an inductance of $L = 30$ mH, and a rated current of 3 A.



Design an unipolar **driver circuit** such that the electrical time constant is 2 ms at phase turn-on and 1 msec at turn off. The stepping rate is 300 steps per second.

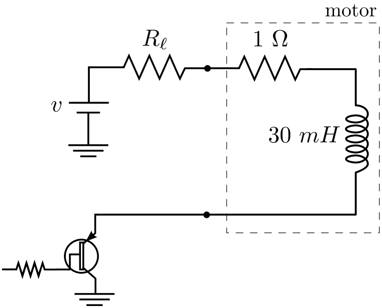
Exercise 52 - continued

(a) Turn-on and turn-off time constants



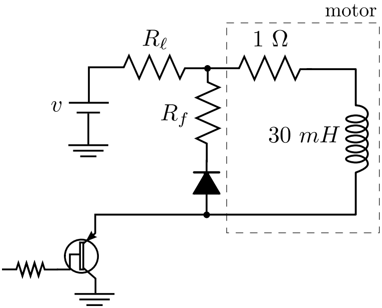
Exercise 52 - continued

(b) Turn-on time constant of 2 ms



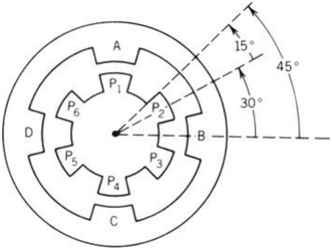
Exercise 52 - continued

(c) Turn-off time constant of 1 ms



Exercise 53

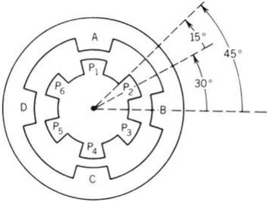
Consider the reluctance motor shown.



(a) Determine the sequence of activation for a 30° step

(b) Determine the sequence of activation for a 15° step

Exercise 53 - continued



Exercise 54

A stepper motor is to be designed to meet the following requirements:

$\rightarrow$ The stator must have 4 phases

$\rightarrow$ The required step size is 18°

Determine the number of rotor poles and the sequence of excitation of the stator phases. Draw a cross-sectional view of the stepper motor.

Exercise 54 - continued

Exercise 55

A two-pole (1 pair) bipolar permanent magnet motor requires six steps per revolution.

(a) Determine the number of stator phases

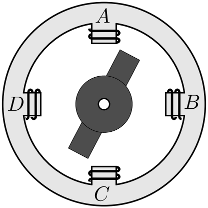
(b) Determine the sequence of excitation

(c) Draw a cross-sectional view of the motor

Exercise 55 - continued

Exercise 56

The variable reluctance motor is controlled by a 4-bit digital signal from a micro-controller. The 4-bits represent the excitation of phases A to D, respectively. For instance, a digital signal 1000 will cause excitation of phase A and 0110 will cause excitation of phase B and C.

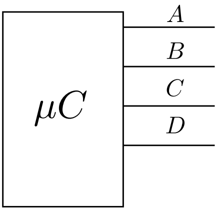


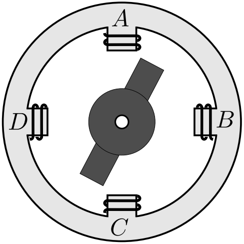
(a) Draw the power circuit to interface the motor with the controller using a unipolar configuration.

(b) Write a table for the 4-bit digital signals for 45° step rotation. Show the angle of rotation and the phase(s) exited.

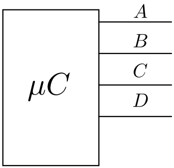
(c) Continuous sequencing causes the motor to rotate at a constant speed. What is the number of pulses per second is the motor rotates at 720 rpm ?

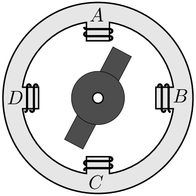
Exercise 56 - continued





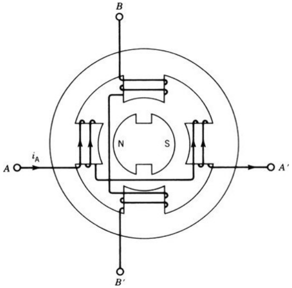
Exercise 56 - continued





Exercise 57

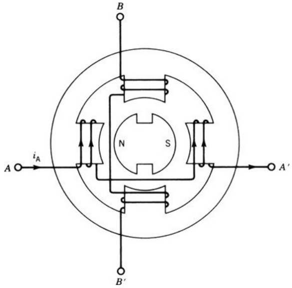
The four-phase permanent magnet stepper motor is excited by a 4-bit digital signal from a microcomputer.



(a) Write a table for the 4-bit digital signals for a 90° step revolution

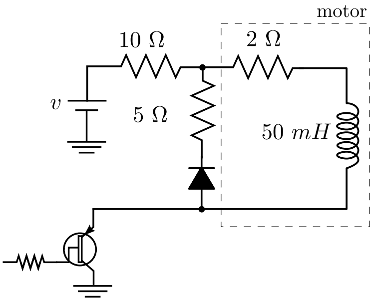
(b) Determine the motor speed if the number of pulses per second is 100.

Exercise 57 - continued



Exercise 58

Each phase of a 3-phase variable reluctance stepper motor has a rated winding current of 5 A and is controlled by a unipolar drive circuit.



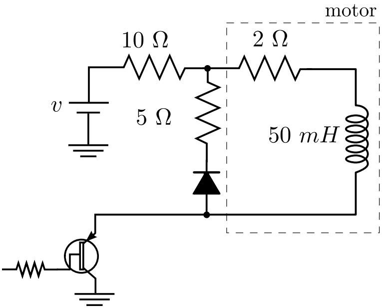
(a) Determine the electrical time constant at turn-on and turn-off of a phase.

(b) Determine the supply voltage v_s

(c) If a phase conducts for $\tau_{on} + \tau_{off}$ seconds, what is the maximum value of the stepping rate (pulses per second) of the coil?

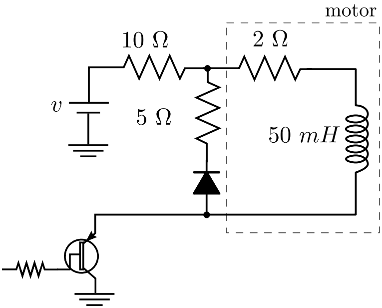
Exercise 58 - continued

(a-b) Time constant and supply voltages



Exercise 58 - continued

(c) Maximum steps per second



Next class...

- DC motors

Additional supporting materials for Lecture 12:

Modelling a stepper motor: `https://goo.gl/61gCja`

Stepper motor with Arduino: `https://goo.gl/ywsZ22`

Unipolar *vs* bipolar stepper motor: `https://youtu.be/Qc8zcst2blU`

Matlab model of a hybrid stepper motor: `https://goo.gl/SjMUHb`