MECH 420

Sensors and Actuators

Presentation Part 9

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Part 9

Stepper Motors

Plan

- The purpose of actuators
- Types of actuators
- Types of stepper motors: Variable-reluctance (VR), Permanent-magnet (PM), Hybrid (HB)
- Toothed rotor and stator
- Design consideration
- Stepper motor control
- Electronic damping of a stepper motor
- Motor selection
- Advantages and disadvantages

Purpose of Actuator

- Actuator mechanically drives/moves a device
- Process actuator drives a plant (e.g., machine, robot)
- Control actuator drives a control device

  (e.g., valve, switch, relay)
- Two General Categories:

  1. Incremental-drive actuators

  2. Continuous-drive actuators

Incremental-drive Actuator:

Moves in increments (steps)

Continuous-drive Actuator:

Moves continuously

Types of Actuators

- **Incremental-drive actuators: Stepper motors – interpreted as digital actuators**
- **Continuous-drive actuators**
  - **DC Motors (Brushed, Brushless)**
  - **AC Motors (Induction Motors, Synchronous Motors)**
  - **Hydraulic and Pneumatic Actuators (Piston-cylinder drives, Hydraulic motors)**

3-roll Calender Machine with Hydraulic Actuators (produces plastic sheets)

Other examples of actuators?

Stepper Motor

- Moves in steps, in response to a pulse sequence or a digital command
- Three basic types of stepper motors
  - Permanent magnet (PM) stepper motor: **Has magnetized rotors**
  - Variable reluctance (VR) stepper motor: **Has soft-iron (ferromagnetic) rotors**
  - Hybrid (HB) stepper motor:

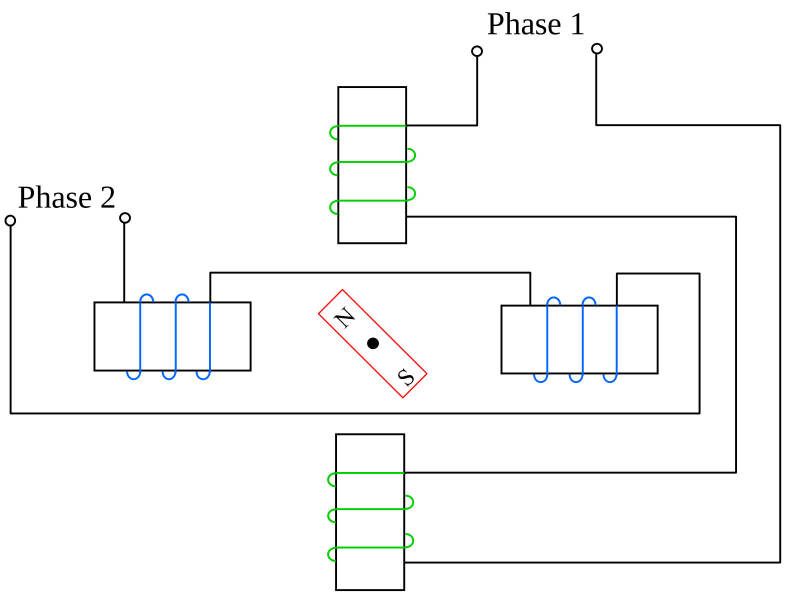
Have two stacks of rotor teeth

forming the two poles of PM

located along rotor axis

Stepper Motor Types

Permanent Magnet Stepper Motor



Full Stepping: Only 1 phase is on at a time

Half Stepping: One or two phases may be on at a time, in sequence

- **Stator: 2 sets of windings – 2 phases at 90º ➔ 4 salient poles**
- **Rotor: 2 pole permanent magnet**
- **Each phase can take 3 states**
  - **State 1: Current in a specified direction**
  - **State -1: Current in the reverse direction**
  - **State 0: No current**

Why is –ve current needed?

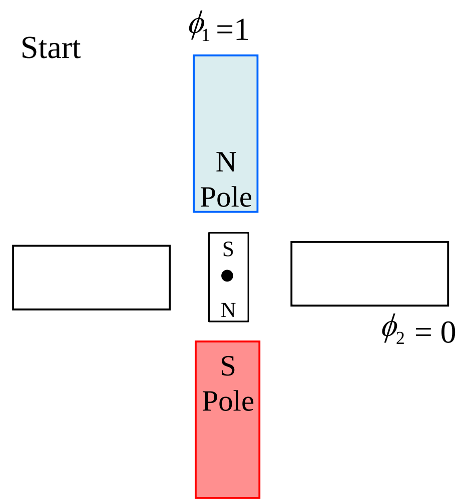
Example: Switching Sequence in Half-stepping

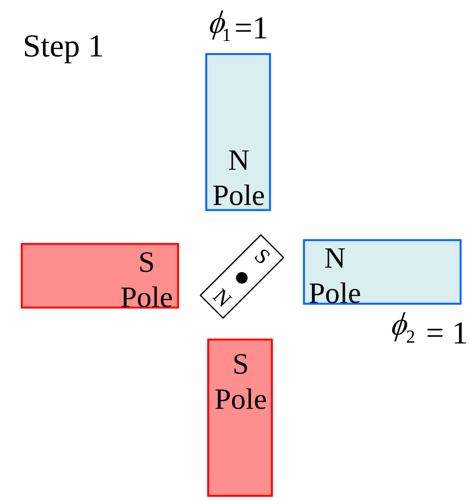
- Switching currents in 2 phases → CW or CCW rotation
- At the end of a step, rotor assumes minimum reluctance position (Stable equilibrium configuration - Detent position)

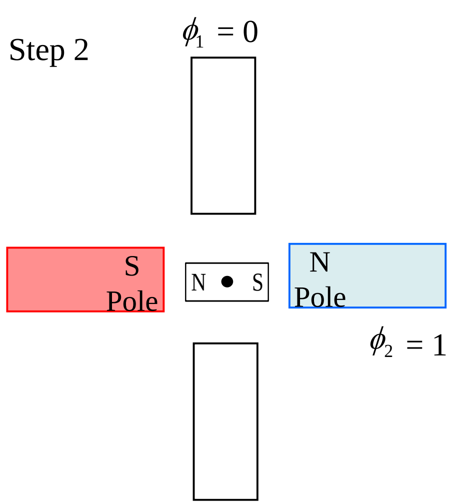
Step No.	ϕ_1	ϕ_2
1	1	1
2	0	1
3	-1	1
4	-1	0
5	-1	-1
6	0	-1
7	1	-1
8	1	0

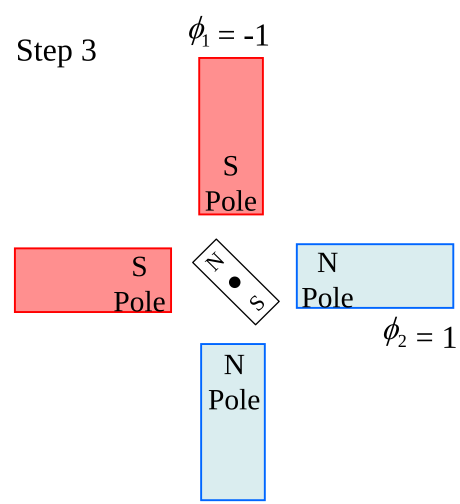
CCW

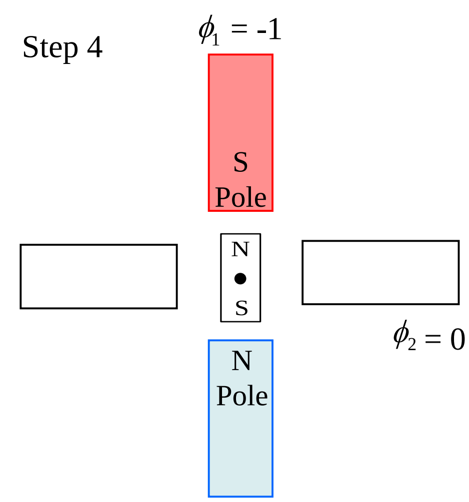
CW







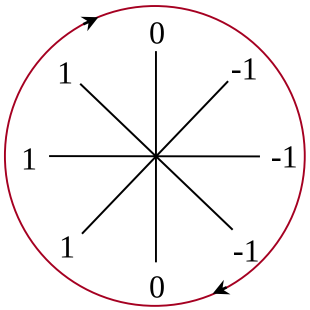


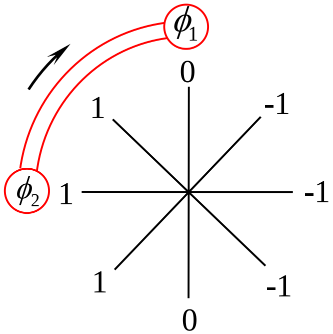


Example: Switching Sequence (Cont'd)

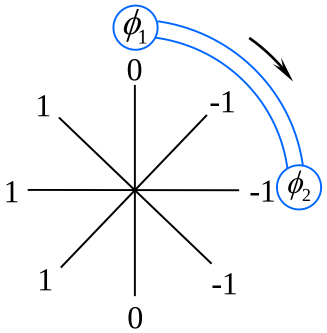
- **Shown switching sequence:** Half stepping; step angle = 45º
- Full stepping: Step angle = 90º
- In full stepping, only one phase is energized at a time
- In half stepping, one or both phases are energized in alternate steps
- Switching logic can be generated by a look-up table
- For clockwise: Stator ϕ_2 lags ϕ_1 by two steps;

  For counter clockwise: ϕ_2 leads ϕ_1 by two steps
- Only one set of numbers with and **"delay logic"** are necessary
- **Indexer:** Generates the pulse sequence
- **Driver (with Translator):** Activates phases according to pulses & logic



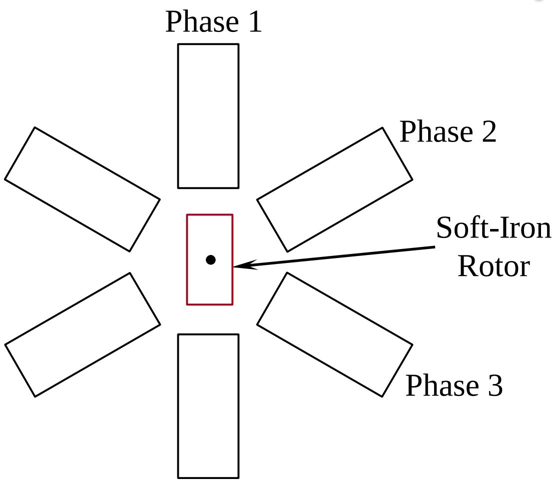


For CW rotation



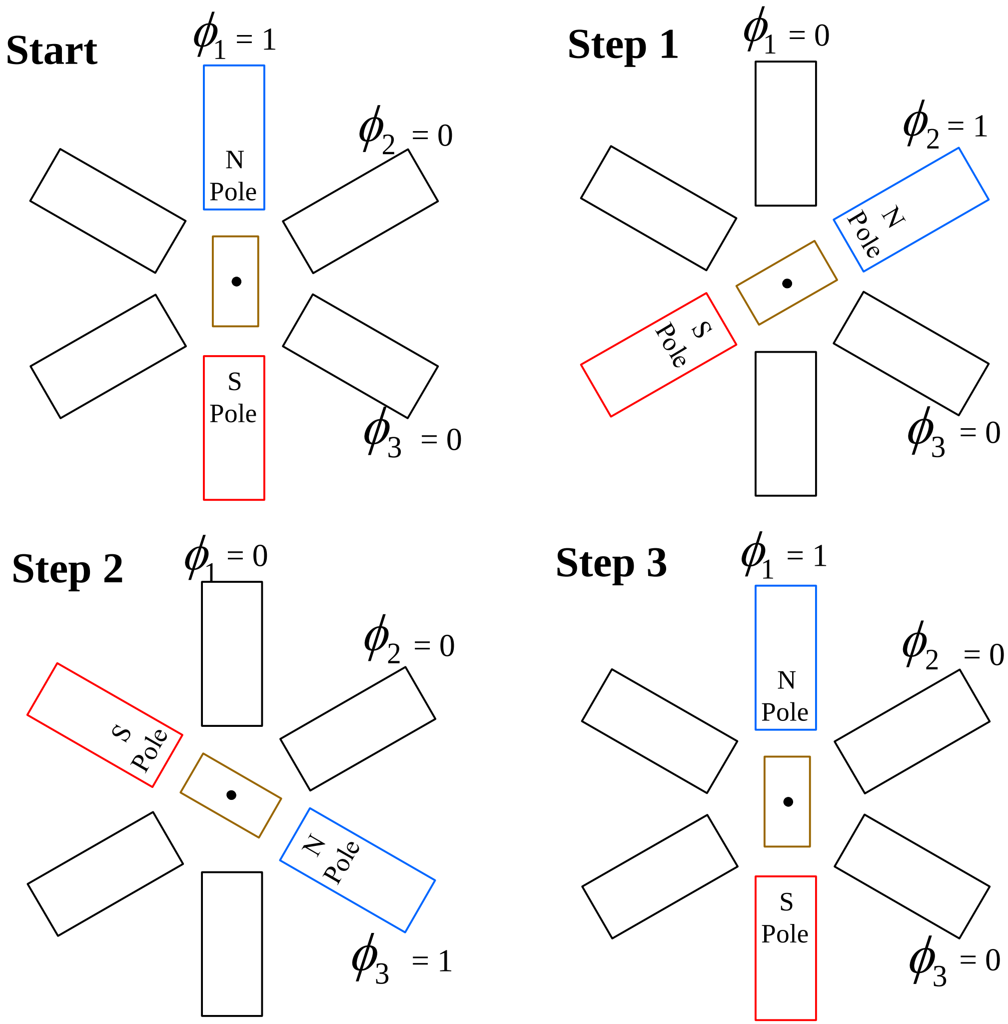
For CCW rotation

Variable Reluctance Stepper Motor



- **Rotor: Non-magnetized soft-iron bar**
- **3 phases are necessary for the shown geometry**
- **Full stepping angle = 60^o; half stepping angle = 30^o**
- **Full stepping: Only 1 phase is energized at a time**
- **Half stepping: Simultaneous energization of 2 phases is necessary (one phase and both phases alternately)**

Full Stepping Sequence for the VR Stepper Motor

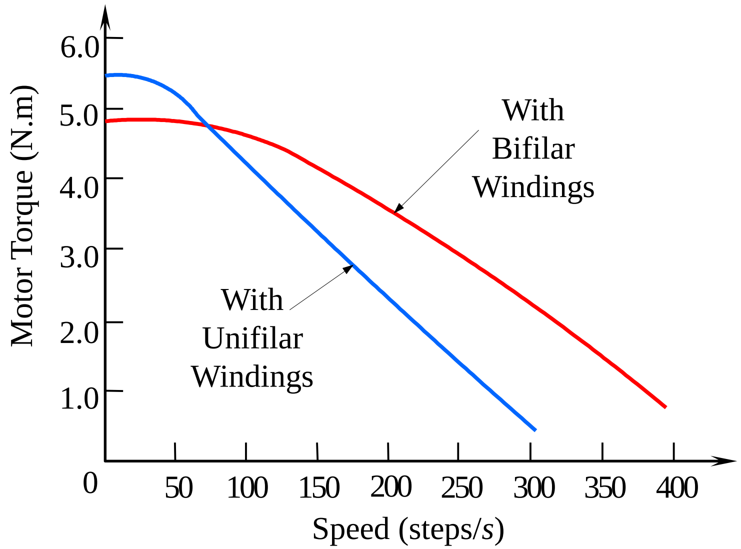


Issues of Polarity Reversal

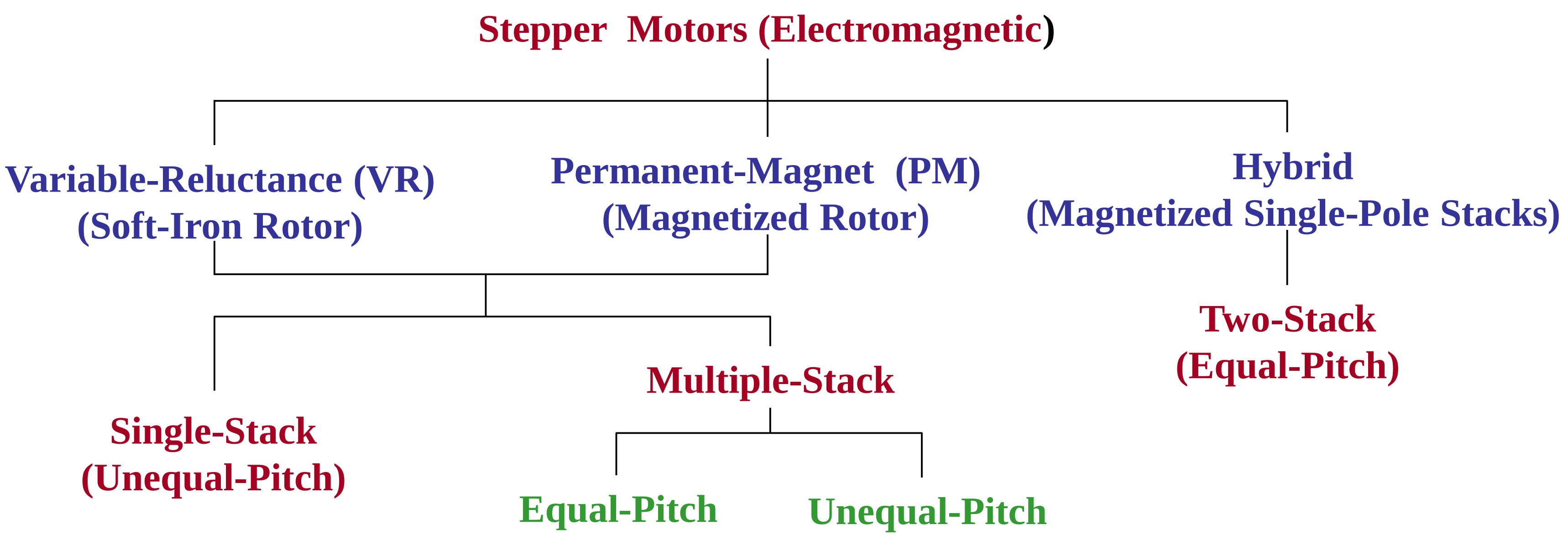
- **Motor Operation:** Phases (i.e., stator windings or field windings) are switched in sequence
- Phase reversal is needed in some stepping sequences. **Methods:**
  - **Unifilar windings** (one set of windings): Reverse the current direction
  - **Bifilar windings** (two sets of windings): Switch the winding

For a given torque rating: Bifilar ➔ twice the number of windings (half of them are inactive at a time)

- **Bifilar:** Motor size increases to accommodate extra windings, friction increases ➔ Reduced **starting torque**
- **Unifilar:** Switching speed increases with motor speed ➔ significant **self-induced** voltages ➔ Degradation of torque at high speeds



Stepper Motor Classification



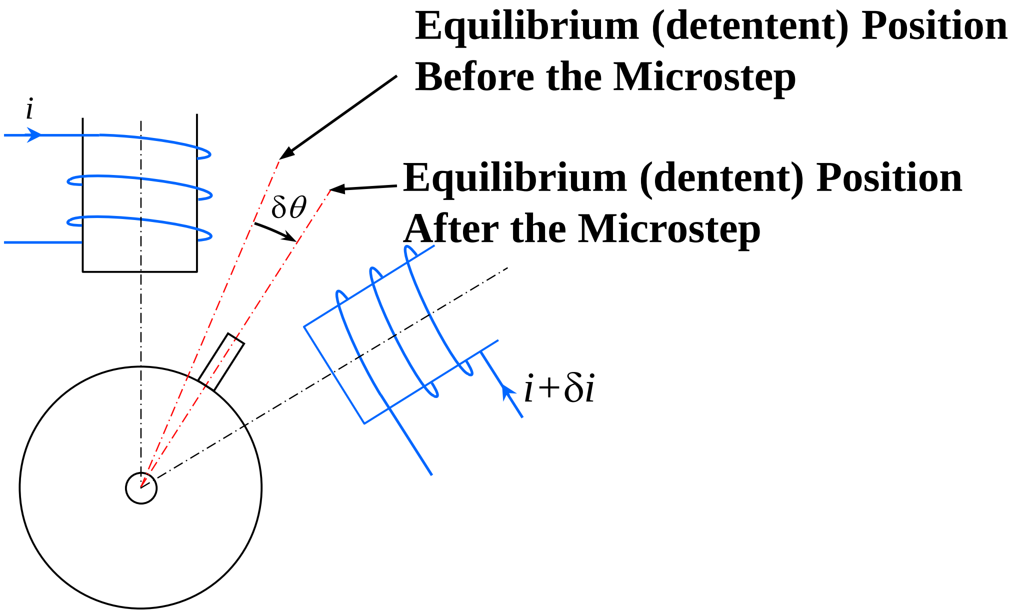
- **An advantage of PM steppers:** They have a holding torque even when phases are not energized
- **Hybrid steppers:** Have two PM stacks of opposite polarity
- **Single stack steppers:** Rotor tooth pitch ≠ stator tooth pitch
- **Multiple stack steppers:** Stator and rotor tooth pitch can be equal but rotationally shifted (misaligned)

Stepper Motor Operation

Stepper Motor Operation

- A magnetic torque has to be created in each detent position, to pull the rotor to the next detent position
- This is done by rotating the resultant magnetic field through phase switching
- A physical misalignment between the rotor poles and the stator poles can further help this process
- “Toothed” construction of rotor and stator will enhance the torque
- Many arrangements are possible (also depends on whether PM, VR, or HB)

Micro-stepping



Method: Change phase current in micro-steps wrt adjacent phase

- Step angles of 1/125 of a full step or 10,000 steps/rev may be achieved
- Accurate motion capabilities and smoother operation
- More costly

Toothed Single-stack Stepper

Stepping needs physical misalignment of stator and rotor teeth

Angular misalignment per pitch = $|\theta_s - \theta_r|$

θ_s **= stator tooth pitch;** θ_r **= rotor tooth pitch;**

Requirements:

1. Total misalignment over 360° **of stator must be (at least) one complete pitch**

2.A This must be equally distributed among stator phases

Total number of teeth pitch in entire stator = $\dfrac{360^\circ}{\theta_s}$

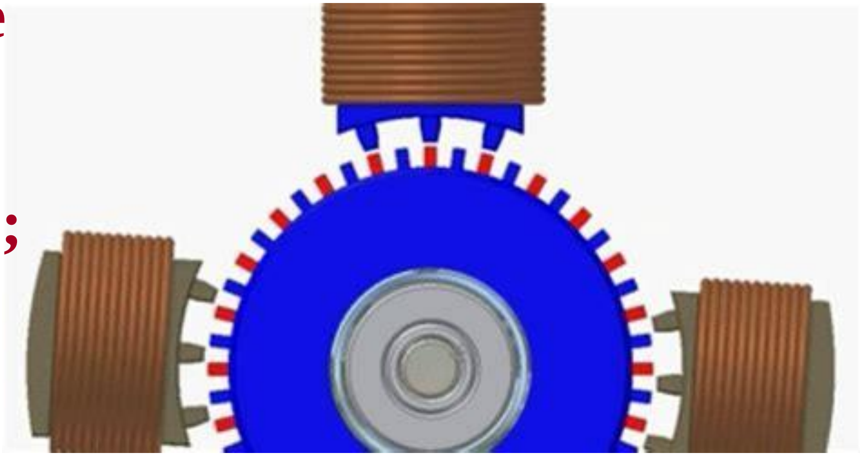
Number of stator teeth pitch in two adjacent phases = $\dfrac{360^\circ}{\theta_s \times p}$

p **= number of phases (number of stator pole pairs)**

Step angle = misalignment between stator and rotor teeth per phase, $\Delta\theta = |\theta_s - \theta_r| \times \dfrac{360^\circ}{\theta_s \times p}$

Note**: This result is for full stepping. For half stepping (one and two adjacent phases are activated alternatively), use half**

Toothed Single-stack Stepper Question



4 Phase, Single Stator Pole per Phase (see figure), p = 4, rotor has 50 teeth.

Questions: 1. What is the step angle?;

2. What is the stepping rate for a motor speed of 300 rpm?

Answers:

Total tooth misalignment angle around the entire stator = θ_s

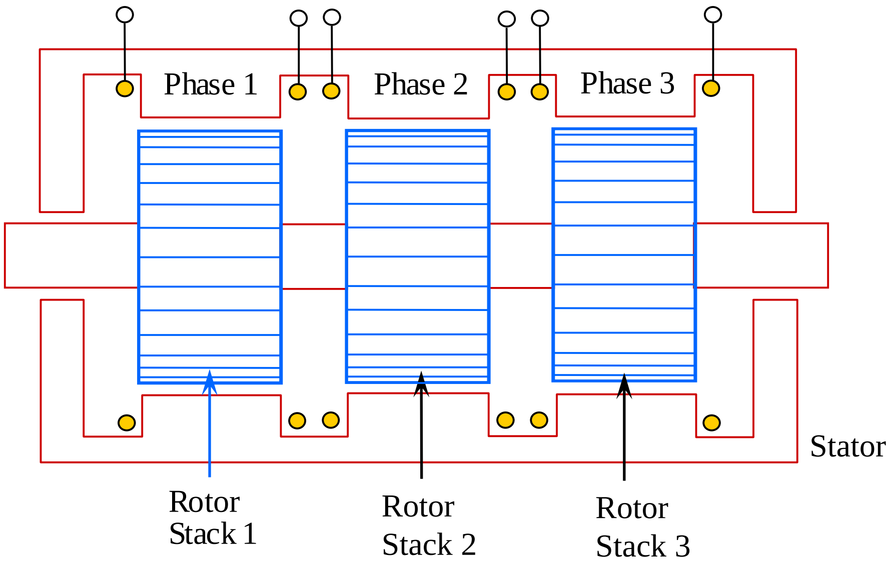
Fraction of this between two adjacent phases = $\dfrac{90^\circ}{360^\circ} = \dfrac{1}{4}$

Step angle $\Delta\theta = \dfrac{\theta_s}{4}$; $\theta_r = \dfrac{360^\circ}{50} = 7.2^\circ \simeq \theta_s$ →

$\Delta\theta = \dfrac{7.2^\circ}{4} = 1.8^\circ$ → **Steps/rev =**

Stepping rate =

Multi-stack Stepper Motors



For this example:
 # phases *p* = 3
 # stacks *s* = 3

- **Both equal pitch and unequal pitch constructions are possible.**
- **Unequal pitch construction ➔ Smaller step angles**
- **Equal pitch case: A stator segment has several poles; all poles of a stator segment are wound to same phase (more common)**
- **Physical Misalignment Methods:**
  1. **Teeth in stator segments are aligned; teeth in rotor segments are misaligned consecutively by 1/3 pitch angle**
  2. **Teeth in rotor segments are aligned; teeth in stator segments are misaligned consecutively by 1/3 pitch angle**

Multi-stack Stepper Motors (Cont'd)

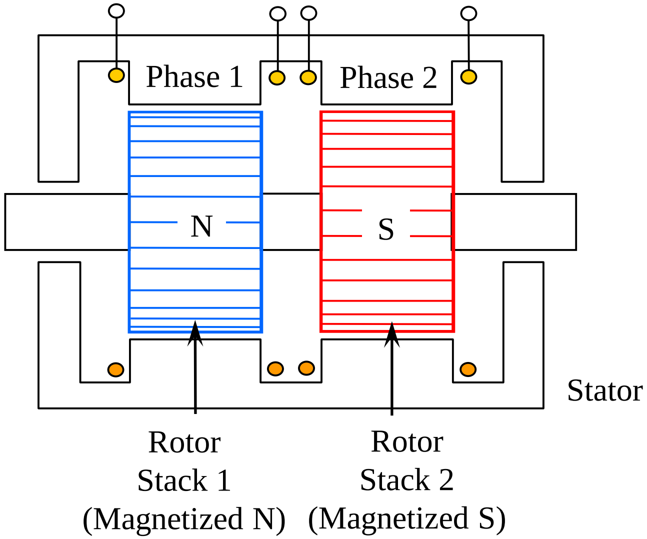
- Both full stepping and half stepping can be achieved
- **Full stepping:** Step angle = misalignment angle

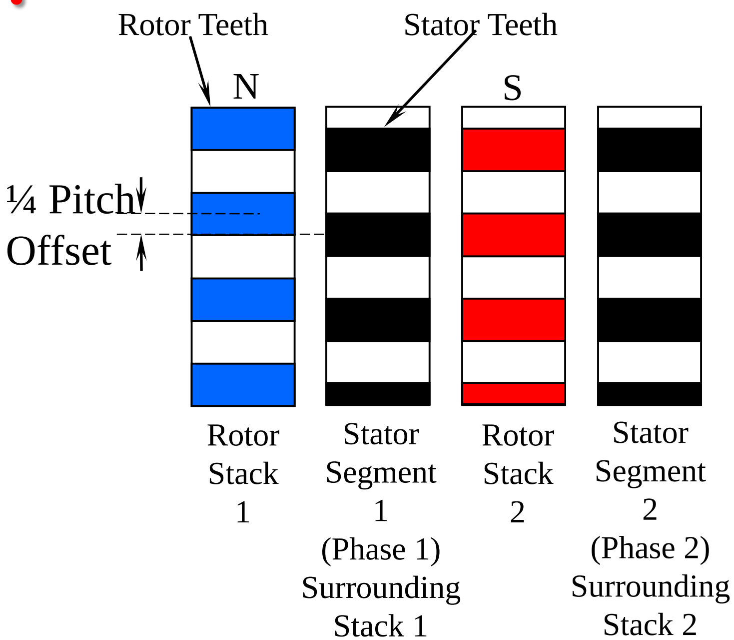
  Stepping sequence 1-2-3-1 → one direction of rotation;

  1-3-2-1 → opposite direction
- **Half stepping:** 1-12-2-23-3-31-1 and 1-13-3-32-2-21-1

- Full stepping angle = misalignment:
- For the given example: $\Delta\theta = \frac{\theta}{3}$

Hybrid Stepper Motor

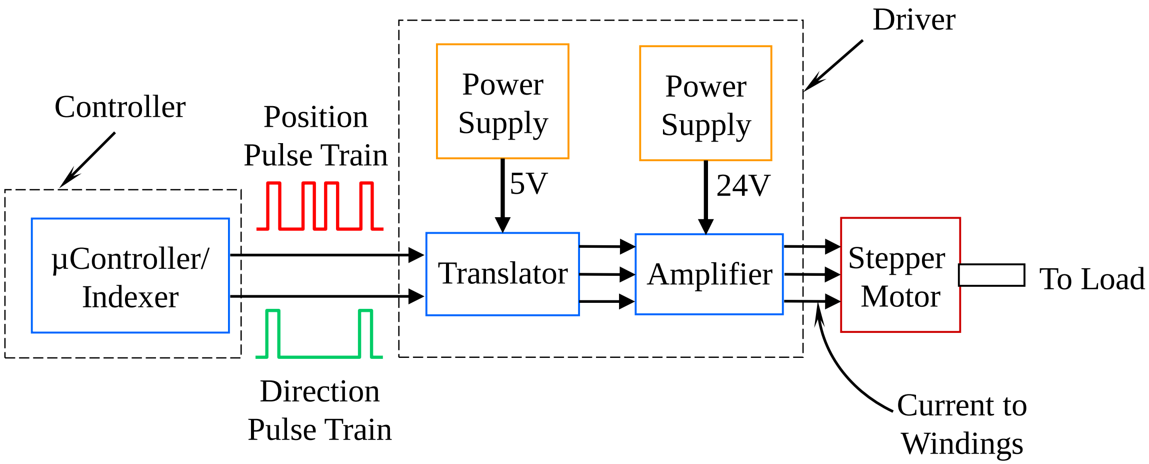




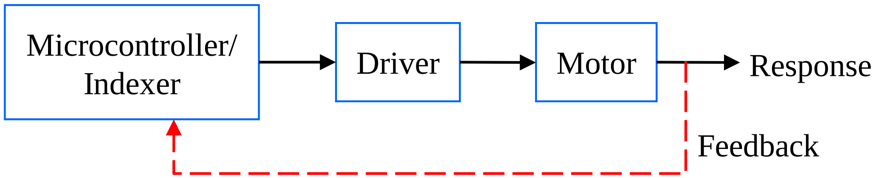
- **Most common variety; 2 rotor segments are magnetized N and S**
- **Both stator and rotor have teeth; stator and rotor pitch angles are equal**
- **Each stator segment is wired to same phase; Inter-stack misalignment = ¼ pitch**
- **Full cycle of switching sequence: [0,1],[-1,0],[0,-1],[1,0],[0,1]**
- **Step angle (full stepping) = misalignment:** $\Delta\theta = \dfrac{\theta}{4}$
- **There is holding torque under no power conditions**

Stepper Motor Control

Driver and Controller

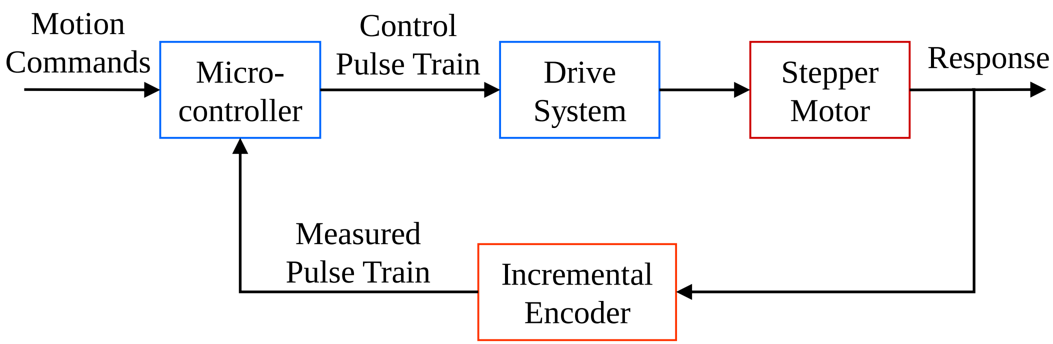


- Microcontroller/Indexer generates pulses: Position, (acceleration and deceleration by changing frequency), and direction
- Translator (phase control logic) converts these pulses into phase activation sequences
- Power amplifier produces currents to energize the phases
- ➔ open-loop control; may not be adequate under some transient conditions due to missing pulses ➔ use feedback control



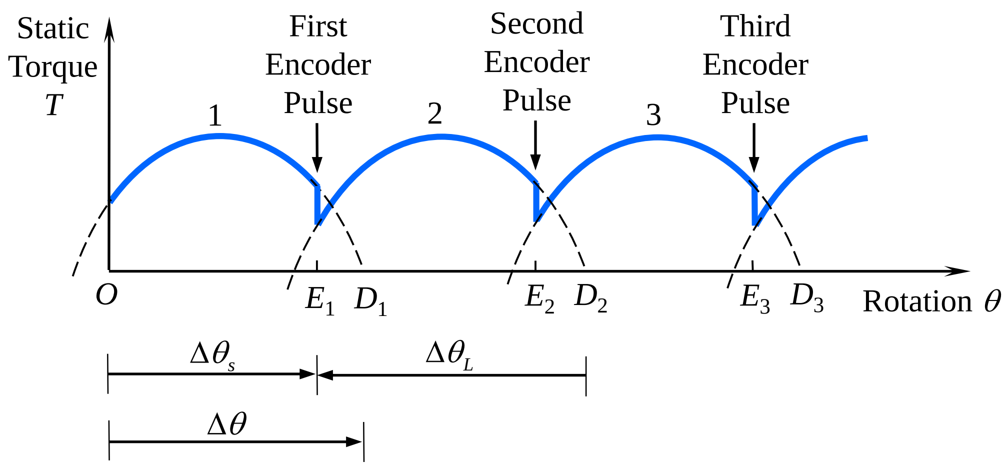
Feedback Control of Stepper Motors

Feedback Encoder-driven Stepper Motor:



- Drive pulses are generated by feedback encoder
- Optical encoder is mounted on rotor shaft
- Particularly useful under acceleration and deceleration conditions

Operation of Feedback Encoder Driven Stepper



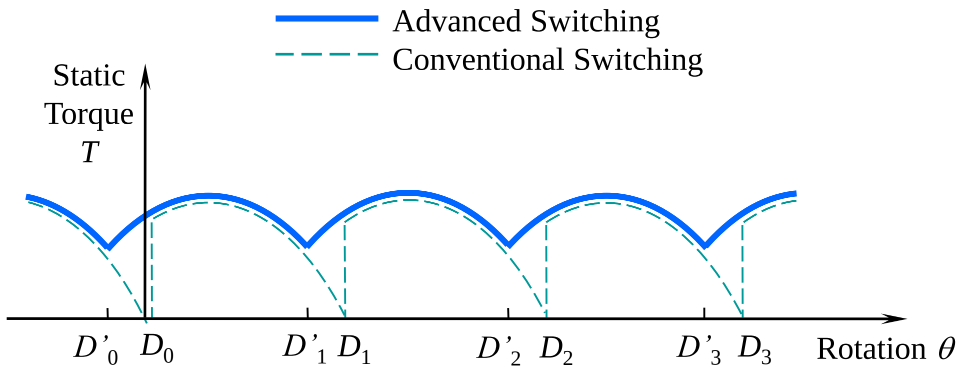
$\Delta\theta_s$ - Switching Angle

$\Delta\theta_L$ - Lead Angle

$$\Delta\theta_s + \Delta\theta_L = 2\Delta\theta$$

- **First pulse is generated externally; subsequent pulses are by the encoder**
- **Encoder orientation is such that 2nd pulse is generated before the detent position of the 1st pulse**
- **➔ Torque is always positive ➔ Motor accelerates until it balances resistive torques (load torque, damping, etc.)**
- **Torque is adjusted by changing the switching position**

Torque Control Through Switching



→ **Higher average torque, by advancing the switching position to the intersecting point of two adjacent torque curves**

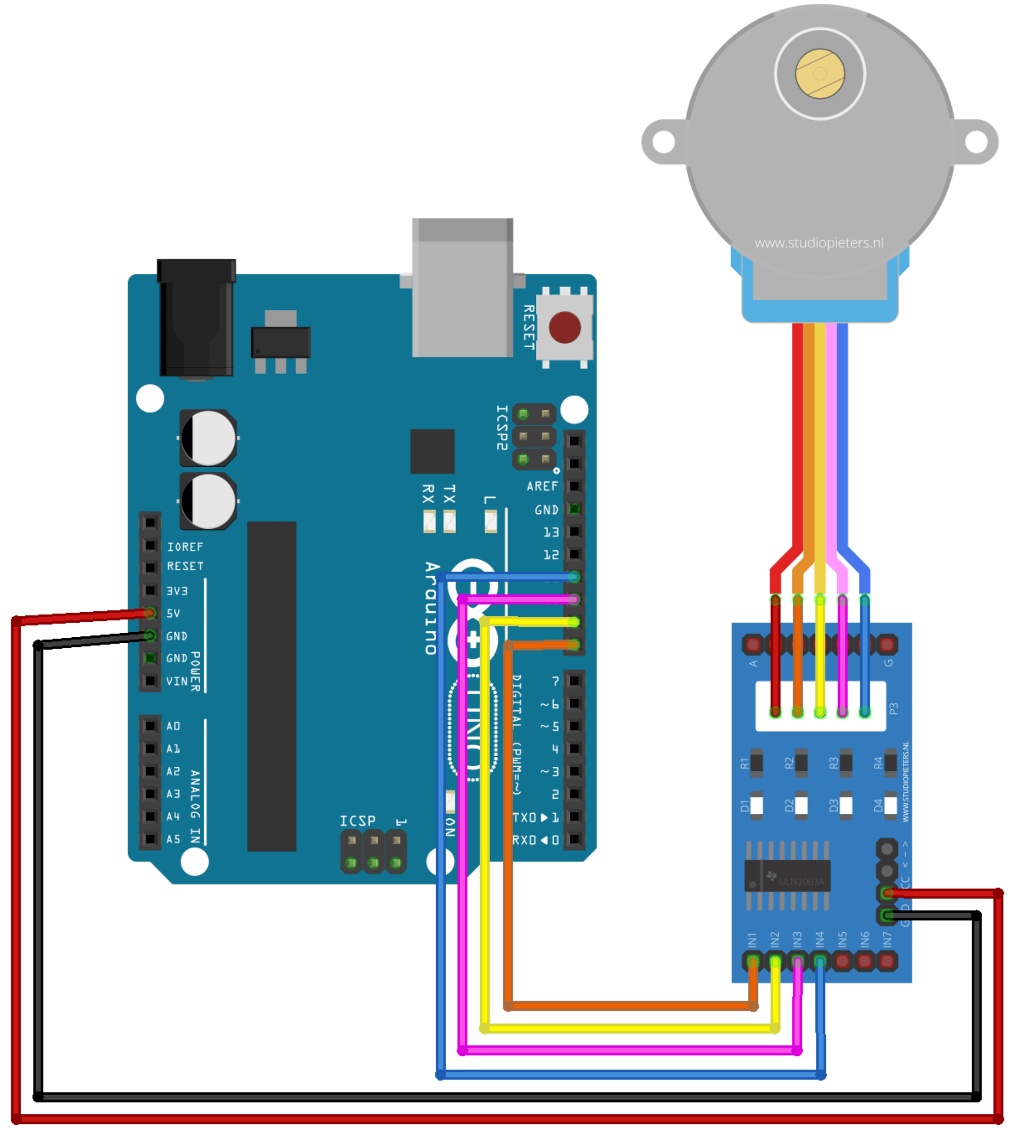
Question

A driver module is used because the controller module (e.g., Arduino) may not be able to provide enough Current from its I/O pins.

Driver Module: ULN2003

Wiring Diagram:
28BYJ-48 Stepper Motor
ULN2003 Driver Module
Arduino Uno Microcontroller

4 phases (4 coils) of the stepper motor are driven using pins 8,9,10 and 11 of Arduino



Question (Cont'd)

Stepper Motor Specs: Rated Voltage 5V DC; 4 phases

What do the 6 wires represent? Hint: Red wire needs 5V

Stepping: Energize the 4 pins in sequence.

Phase 1: Pin 8

Phase 2: Pin 9

Phase 3: Pin 10

Phase 4: Pin 11

How do you achieve:

(a) Full stepping?

(b) Half stepping?

(c) Direction reversal?

***Note*: The rotor aligns along the resultant magnetic field of stator.**

Half stepping can produce ~40% more average torque

Stepper Motor Selection (Sizing)

Stepper Motor Terminology

Detent Position: Equilibrium position or Minimum reluctance position corresponding to the magnetic field pattern in the stator

Stand-Still (Stalling) Torque: Torque at zero speed, from (steady-state and averaged) speed-torque characteristic of stepper motor

Residual Torque: Maximum static torque when the motor phases are not energized; Negligible for VR motor, not for a PM or HB motor

Detent Torque: One definition: Same as residual torque ➔ torque ripple present when power off conditions. Better definition: Static torque at present detention position (equilibrium position) when the next phase is energized ➔ T_{max} sin $2\pi/p$ = holding torque , p = number of phases (defined under power-on conditions)

Holding Torque: Maximum static torque ➔ max torque motor needed to start rotating. In some literature: detent torque = holding torque, under power-on conditions. When power off, VR motors have negligible holding torque

Stepper Motor Terminology (Cont'd)

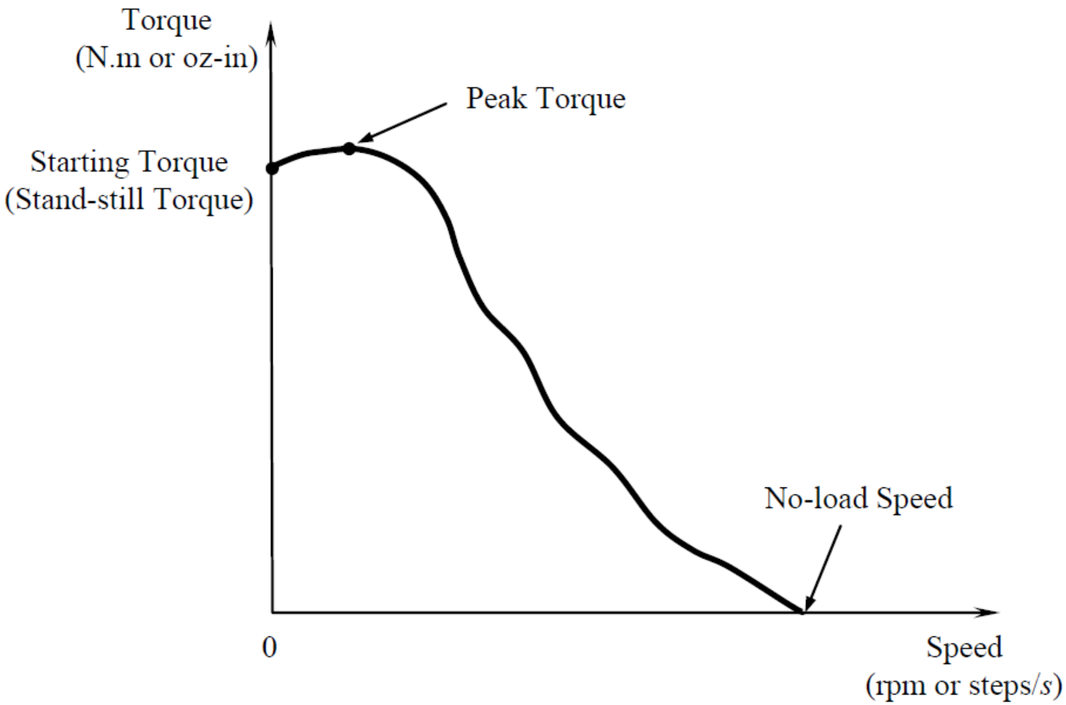
Pull-out Curve (Slew Curve): Speed at which motor runs under steady conditions, under rated current and using appropriate drive circuitry ➔ *pull-out torque* and *pull-out speed*

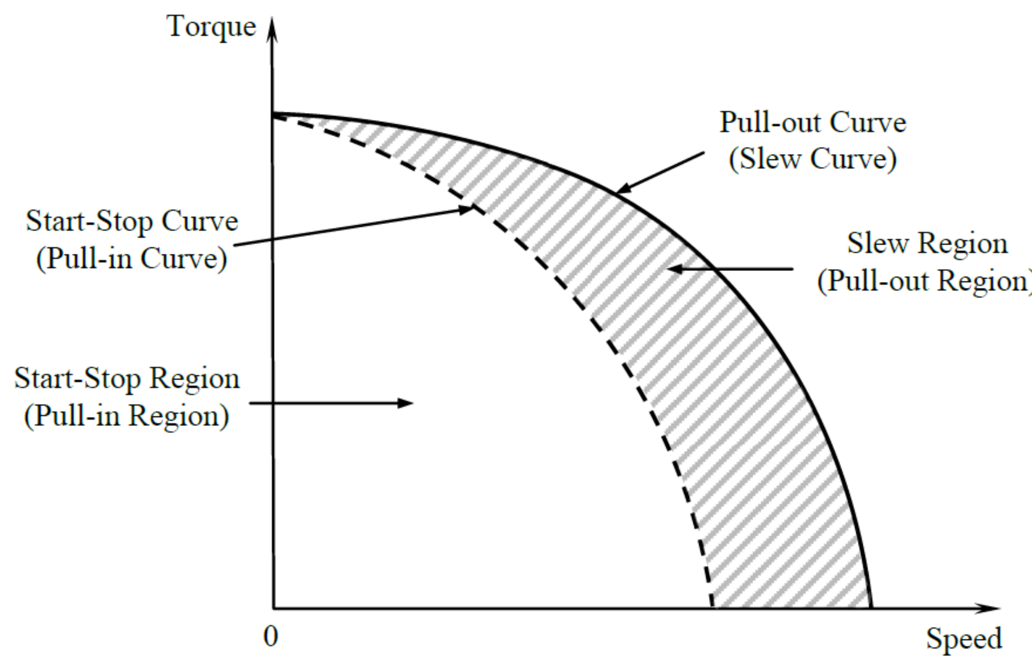
Pull-out Torque: Maximum torque that has to be be applied (using an acceleration ramp) to accelerate the motor without losing synchronism (without losing steps or stalling). Maximum pull-out torque = starting torque (stand-still torque)

Pull-in Torque: The maximum torque that can be maintained by the motor under normal operating conditions, in synchronism with the pulses (i.e., without losing steps)

***Note*: Pull-out torque > Pull-in torque (can be greater by25% or more)**

Stepper Motor Characteristics





Stepper Motor Selection (Sizing)

- **Problem:** Matching of motor with application (process, plant) requirements
- Drive system has to be chosen as well to match the motor
- **Need:** Torque vs. stepping rate curve (i.e., pull-out curve)
- Other Parameters Useful in Motor-selection parameters:

1. Step angle (or, number of steps per revolution)
2. Static holding torque (max static torque when powered at rated voltage)
3. Maximum slew rate (max steady-state stepping rate possible at rated load)
4. Motor torque at required slew rate (pull-out torque, found in pull-out curve)
5. Maximum ramping slope (max acceleration & deceleration possible at rated load)
6. The motor time constants (no-load electrical time constant and mechanical time constant)
7. Motor natural frequency (without an external load and near detent position)
8. Motor size (dimensions of: poles, stator and rotor teeth, air gap and housing; weight, rotor moment of inertia)
9. Power supply ratings (voltage, current, and power)

Stepper Motor Selection (Sizing) Steps

Depends on: Particular application, torque and speed considerations, geometric properties

Guidelines for Selection Process

- ***Step 1:*** List main requirements for particular application – speed, acceleration, accuracy, resolution, load characteristics
- ***Step 2:*** Compute operating torque and stepping rate requirements for particular application (Newton's 2nd law)

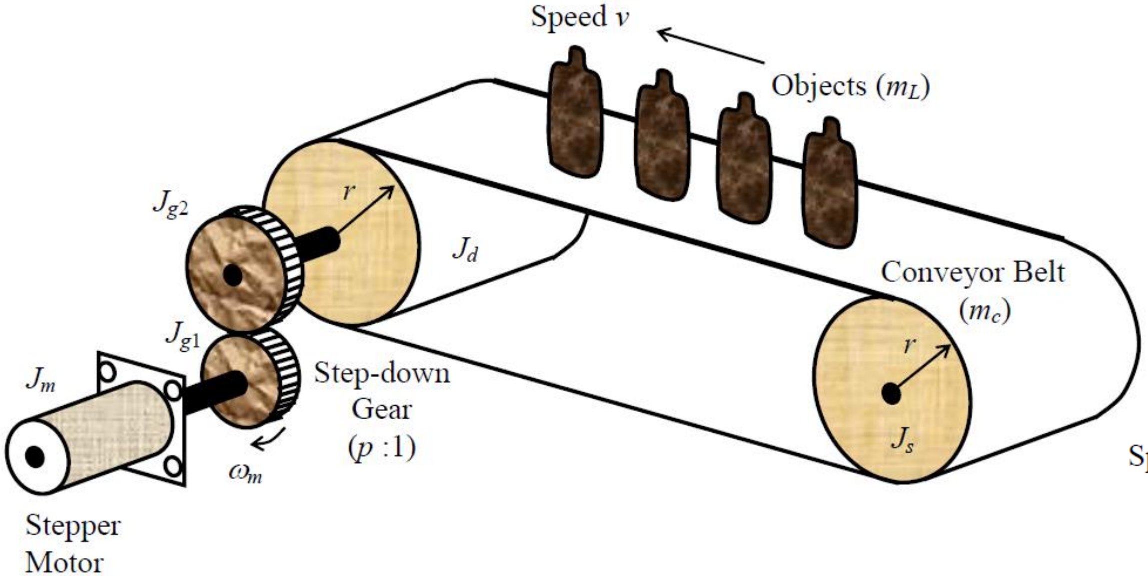
$$T = T_R + J_{eq} \frac{\omega_{\max}}{\Delta t}$$

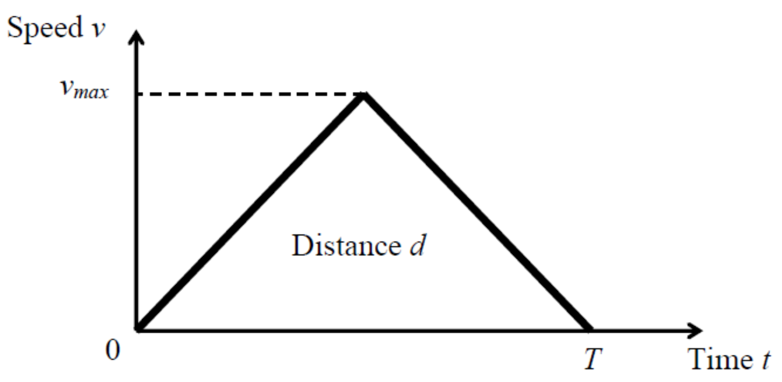
T_R = net resistance torque
J_{eq} = equivalent moment of inertia (including rotor, load, gearing, dampers, etc.)
$\omega_{\max}$ = maximum operating speed
Δt = time taken to accelerate the load to maximum speed, starting from rest (i.e., ramping up)

- ***Step 3:*** Using torque vs stepping rate curves (pull-out curves) for a group of commercially available stepper motors, select a suitable stepper motor (Use torque and speed requirements of Step 2, and accuracy and resolution requirements of Step 1). Redo Steps 2 and 3 after adding *motor inertia*
- ***Step 4:*** If a stepper motor that meets the requirements is not available, modify the basic design (e.g., incorporate a gear transmission)
- ***Step 5:*** Select a drive system that is compatible with the selected motor (motor supplier and product literature will assist in this)

Example 8.9: Product Conveyor

- Industrial conveyor for product completion, inspection, movement, grading, etc.
- Conveyor moves intermittently at a fixed rate ➔ indexes objects through distance *d* in time period *T*
- A triangular speed profile is used for each motion interval, with equal acceleration and a deceleration
- A gear unit with step-down speed ratio *p*:1, *p* > 1, may be used if necessary



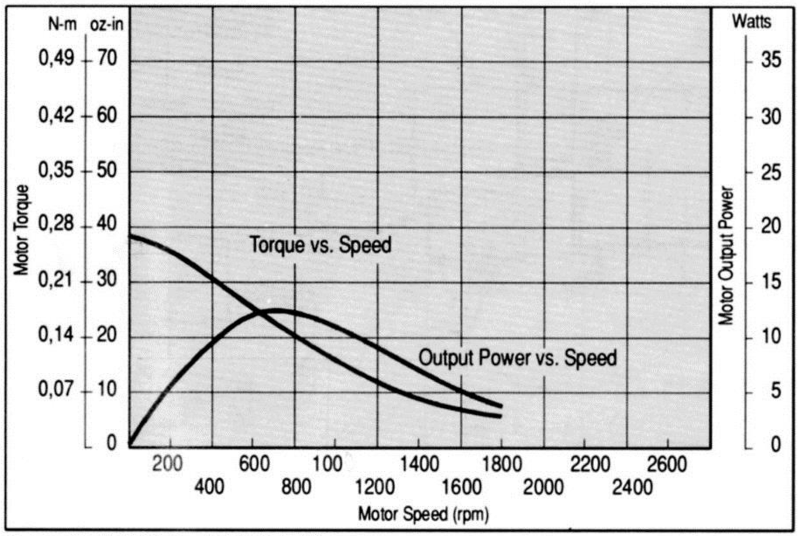


Stepper Motor Data (Example 8.9)

Model		Stepper Motor Specifications			
		50SM	101SM	310SM	1010SM
NEMA motor frame size		23	23	34	42
Full step angle	Degrees	1.8			
Accuracy	%	±3 (noncumulative)			
Holding torque	oz.in	38	90	370	1050
	N.m	0.27	0.64	2.61	7.42
Detent torque	oz.in	6	18	25	20
	N.m	0.04	0.13	0.18	0.14
Rated phase current	Amps	1	5	6	8.6
Rotor inertia	$oz.in.s^2$	1.66×10^{-3}	5×10^{-3}	26.5×10^{-3}	114×10^{-3}
	$kg.m^2$	11.8×10^{-6}	35×10^{-6}	187×10^{-6}	805×10^{-6}
Maximum radial load	lb	15	15	35	40
	N	67	67	156	178
Maximum thrust load	lb	25	25	60	125
	N	111	11	267	556
Weight	lb	1.4	2.8	7.8	20
	kg	0.6	1.3	3.5	9.1
Operating temperature	°C	−55 to +50			
Storage temperature	°C	−55 to +130			

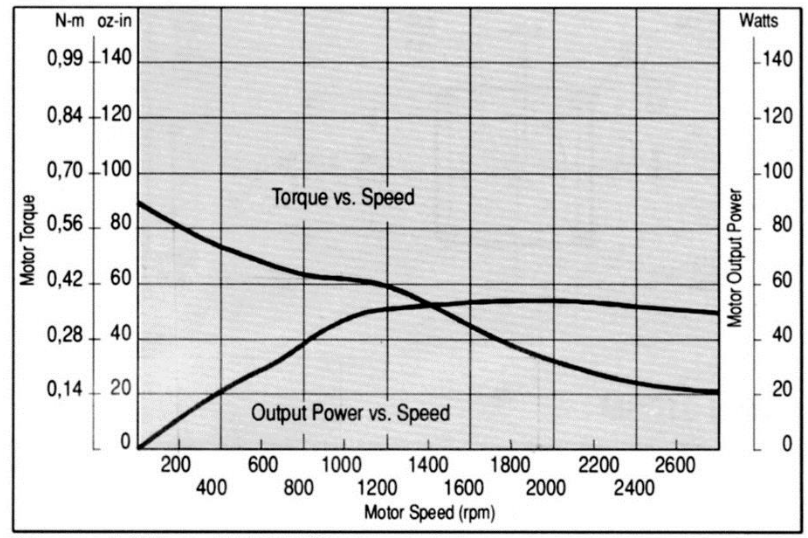
Stepper Motor Characteristics (Example 8.9)

Model 50SM



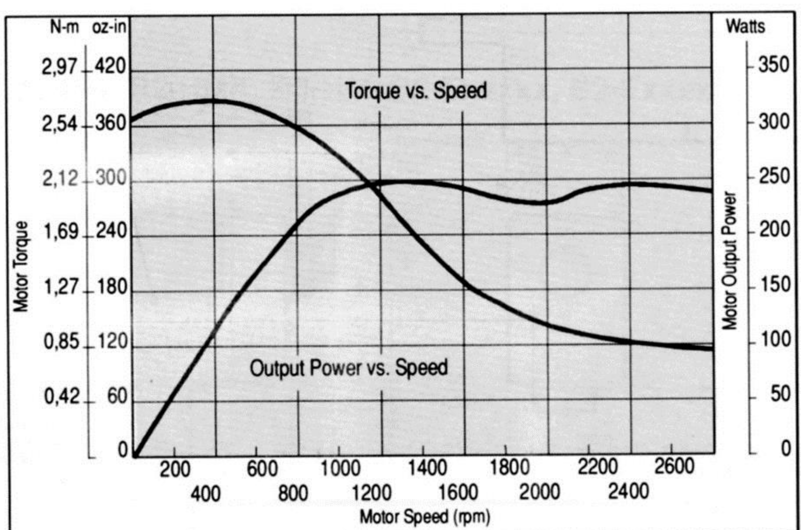
Recommended Drivers : DM4001, U1A

Model 101SM



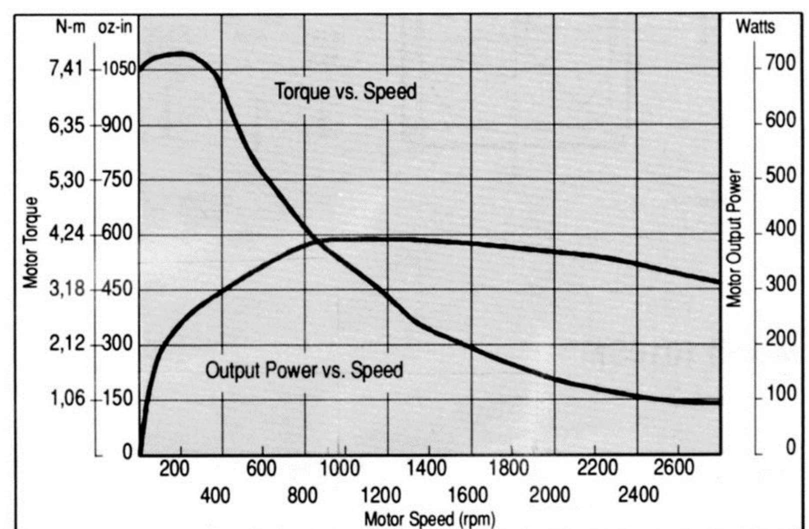
Recommended Drivers: DM4005, U1B

Model 310SM



Recommended Drivers: DM8010, DMV8008, U1D

Model 1010SM



Recommended Drivers: DM16008, DMV16008, U1F

Stepper Motor Selection (Example 8.9)

Equivalent moment of inertia J_e at motor shaft, for the overall system:

$$J_e = J_m + J_{g1} + \frac{1}{p^2}(J_{g2} + J_d + J_s) + \frac{r^2}{p^2}(m_c + m_L)$$

J_m, J_{g1}, J_{g2}, J_d, & J_s: moments of inertia of motor rotor, drive gear, driven gear, drive roller, & driven roller; m_c & m_L: overall masses of conveyor belt and moved objects (load); r = radius of a roller

Given: d = 10 cm, T = 0.2 s, r = 10 cm, m_c = 5 kg, m_L = 5 kg, $J_d = J_s = 2.0 \times 10^{-3}$ kg.m^2

Two gear units: p = 2 & 3; $J_{g1} = 50 \times 10^{-6}$ kg.m^2 & $J_{g2} = 200 \times 10^{-6}$ kg.m^2

What is the positioning resolution of the conveyor (rectilinear) for the final system?

Assume an overall system efficiency of 80% regardless of whether a gear unit is used

Solution:

From triangular speed profile: $d = \frac{1}{2} v_{\max} T$

Substituting numerical values: $0.1 = \frac{1}{2} v_{\max} 0.2 \rightarrow v_{\max} = 1.0 \text{ m/s}$

Acceleration/deceleration of system: $a = \frac{v_{\max}}{T/2} = \frac{1.0}{0.2/2} \text{ m/s}^2 = 10.0 \text{ m/s}^2$

Corresponding angular acceleration/deceleration of motor: $\alpha = \frac{pa}{r}$.

With efficiency η, motor torque T_m needed to accelerate/decelerate the system:

$$\eta T_m = J_e \alpha = J_e \frac{pa}{r} = \left[J_m + J_{g1} + \frac{1}{p^2}(J_{g2} + J_d + J_s) + \frac{r^2}{p^2}(m_c + m_L) \right] \frac{pa}{r}$$

Maximum speed of motor: $\omega_{\max} = \frac{p v_{\max}}{r}$

Without gears (p = 1): $\eta T_m = [J_m + J_d + J_s + r^2(m_c + m_L)] \frac{a}{r}$

Stepper Motor Selection (Example 8.9, Cont'd)

Case 1: Without Gears

For η = 0.8 (i.e., 80% efficient): $0.8T_m = [J_m + 2\times10^{-3} + 2\times10^{-3} + 0.1^2(5+5)]\dfrac{10}{0.1}$ N.m

➔ $T_m = 125.0[J_m + 0.104]$ N.m **and** $\omega_{max} = \dfrac{1.0}{0.1}$ rad/s $= 10\times\dfrac{60}{2\pi}$ rpm $= 95.5$ rpm

Operating speed range: 0–95.5 rpm.

***Note*: Torque at 95.5 rpm < starting torque, for first two motors, not so for other two (See speed–torque curves). In motor selection, use the weakest point (i.e., lowest torque) in the operating speed range**

Without gears, motors cannot meet system requirements (see Table)

Data for Selecting a Motor Without a Gear Unit.

Motor Model	Available Torque at ω_{max} (N.m)	Motor–Rotor Inertia ($\times 10^{-6}$ kg.m^2)	Required Torque (N.m)
50 SM	0.26	11.8	13.0
101 SM	0.60	35.0	13.0
310 SM	2.58	187.0	13.0
1010 SM	7.41	805.0	13.1

Stepper Motor Selection (Example 8.9, Cont'd)

Case 2: With Gears

***Note*: Usually system efficiency drops when gears. Ignore this here.**

With 80% efficiency (η = 0.8):

$$0.8T_m = \left[J_m + 50\times10^{-6} + \frac{1}{p^2}(200\times10^{-6} + 2\times10^{-3} + 2\times10^{-3}) + \frac{0.1^2}{p^2}(5+5) \right] p \times \frac{10}{0.1}\ \text{N.m}$$

and $\omega_{\max} = \frac{1.0\ p}{0.1}\ \text{rad/s} = 10\ p \times \frac{60}{2\pi}\ \text{rpm}$

$\Rightarrow$ $T_m = 125.0\left[J_m + 50\times10^{-6} + \frac{1}{p^2}\times104.2\times10^{-3} \right] p\ \text{N.m}$ **and** $\omega_{\max} = 95.5\,p\ \text{rpm}$

For p = 2: ω_{max} = 191.0 rpm

With p = 2, model 1010 SM satisfies the requirement (see Table)

With full stepping, step angle = 1.8°. Corresponding step in conveyor motion = positioning resolution. With p = 2 and r = 0.1 m, positioning resolution =

$$\frac{1.8^\circ}{2} \times \frac{\pi}{180^\circ} \times 0.1 = 1.57\times10^{-3}\ \text{m.}$$

Data for Selecting a Motor With Gear.

Motor Model	Available Torque at ω_{max} (N.m)	Motor–Rotor Inertia (× 10^{-6} kg.m²)	Required Torque (N.m)
50 SM	0.25	11.8	6.53
101 SM	0.58	35.0	6.53
310 SM	2.63	187.0	6.57
1010 SM	7.41	805.0	6.73

Stepper Motor Advantages

- **Position error is noncumulative. A high motion accuracy possible, even under open-loop control**
- **Cost is relatively low; Considerable savings in sensor system and controller costs possible for open-loop operation**
- **Because of “incremental” command and motion, easily adoptable to digital control applications**
- **No serious stability problems, even under open-loop control (and up to about 2000 pulse (steps)/s)**
- **Torque capacity and power requirements can be optimized and response can be controlled by electronic switching**
- **Brushless construction has obvious advantages**

Stepper Motor Disadvantages

- Low-speed, low-torque actuators. Torque capacity is typically < 15 N.m
- Speed limited by torque capacity and by pulse-missing problems (due to faulty switching systems and drive circuitry)
- High vibration levels due to stepwise motion
- Large errors and oscillations (motor can stall) when pulses missed, in open-loop control
- Thermal problems when operating at high speeds for long periods

***Note*: In most applications, merits outweigh drawbacks**

Question

Step angle 1.8 degrees, 400 pulses/s. What is the motor speed (in full stepping and half stepping)?

Answer:

400 pulses/s = 400x1.8 deg/s

= 720.0 deg/s

= 2 rev/s =120 rpm

Same whether full stepping or half stepping. Why?