PL 7 – Stepper motors: main components and working principles

Objectives:
- Identify industrial stepper motor types and constructions
- Select and justify wiring configurations
- Interpret torque-speed and power-speed curves
- Understand and compare industrial stepper motor drives
- Perform a basic industrial sizing and selection task

Documents available
PL classes: 1) OrientalMotor files 2) 2026 SE_TP(3)Stepper motors.pdf
Web sites:
www.orientalmotor.com/stepper-motors/
www.orientalmotor.com/stepper-motors/technology/stepper-motor-basics.html
www.kollmorgen.com/en-us/products/motors/stepper/
https://en.nanotec.com/products/153-stepper-motors-from-manufacturer

1. **Main Types of Stepper Motors in Industry (see document 2026 SE_TP(3)Stepper motors.pdf)**
   i. **Variable Reluctance (VR) Stepper Motors**
   ii. **Permanent Magnet (PM) Stepper Motors**
   iii. **Hybrid Stepper Motors (Industrial Standard)**
   Hybrid stepper motors combine permanent magnet and variable reluctance principles and represent the **dominant industrial solution**.

i. Complete the following table

Feature	Variable Reluctance (VR)	Permanent Magnet (PM)	Hybrid (HB)
Rotor construction	Soft iron, toothed (no magnets)	Permanent magnet rotor	Toothed rotor with permanent magnet
Typical step angle	1.8°- 15°	3.6°-18°	Small (1.8°, 0.9°, or less)
Torque density	Low	Medium	High
Holding torque (power off)	None	Present	High
Microstepping capability	Limited	Limited	Excellent
Vibration and smoothness	Poor	Moderate	Good (very good with microstepping)
Efficiency	Low	Medium	High
Cost	Low	Low-medium	Medium
Typical sizes	Limited	Small-medium	Standardized industrial sizes (NEMA 17-66)
Industrial relevance today	Rare / obsolete	Limited	Industrial standard
Typical applications	Educational, legacy systems	Simple positioning, consumer devices	Industrial automation, 3D printers, packaging machines

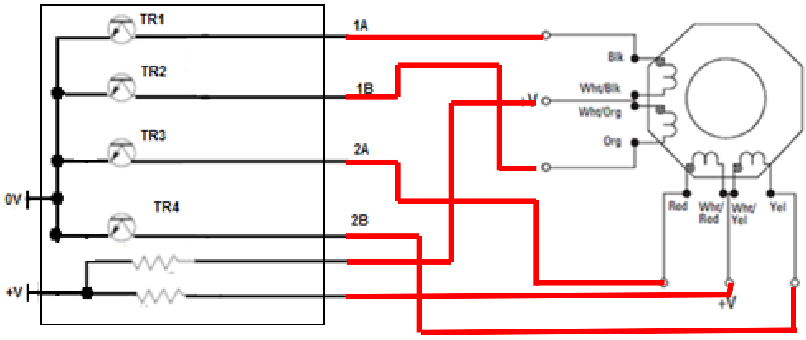
ii. Identify and verify the types of stepper motors available from Oriental Motor
HB____

2. Phases and wiring
   i. 2-phase stepper motors (**industrial standard**)
   Best compromise between cost and performance
   - Motors can be configured to have 4, 5, 6 or 8 wires
   - 2-phase stepper motors are predominantly driven by bipolar, current-controlled (chopper) drivers with **microstepping** capability, using **pulse/direction interfaces** or **industrial communication links**.

ii. 5-phase stepper motors

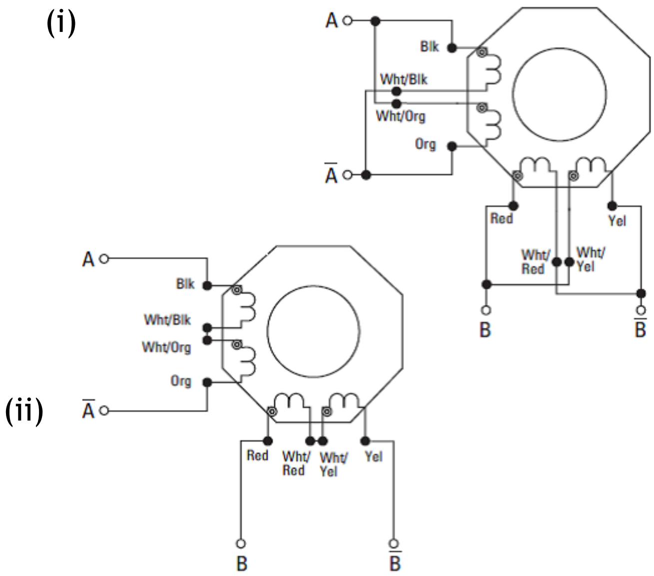
- Five-phase stepper motors are used in industrial applications where smooth motion, low vibration, and high positioning repeatability are more critical than simplicity or cost. Compared with standard two-phase stepper motors, five-phase designs inherently reduce torque ripple and resonance effects due to smaller electrical step angles and increased overlap between excited phases.
- This motor is configured to have 10 wires or in alternative 5 wires
- 5-phase stepper motors are driven by dedicated bipolar, current-controlled 5-phase drivers, specifically designed to generate the required multi-phase excitation sequence, providing smooth motion, low vibration, and high positioning repeatability.

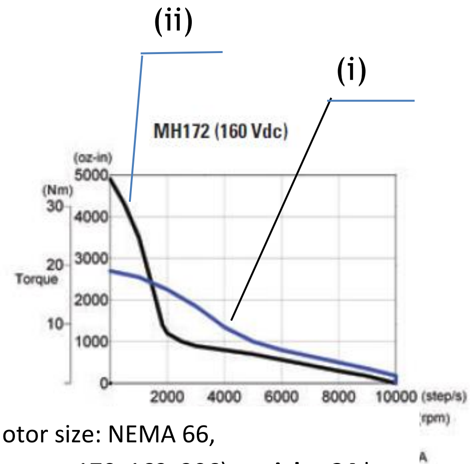
3. Consider the figure below as representative of a unipolar drive for a 2 phases and 6-wire stepper motor. Complete the connections of the drive to the stepper motor.



i. The figures (i and ii) represent 2-phases, 8-wire, stepper motors, with two alternative wires configuration connections. The figure includes a diagram with the characteristic curves (ω-T) for a high torque stepper motor ([Kollmorgen, MH172](#)). Identify the corresponding type of wire connections in the diagram and the associated stall torque:

- wire connections: (i)_parallel__ (ii)__series___
- stall torque: (i)_ [19,4 Nm] or 2750 [oz-in]_ (ii)_ [35,3 Nm] or 5000 [oz-in]

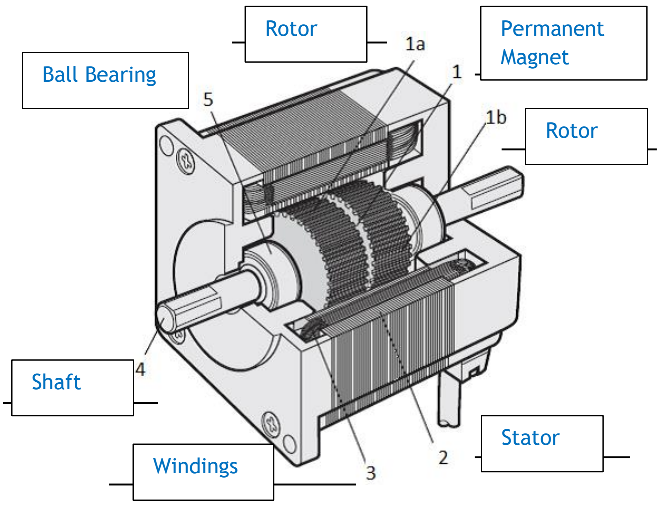


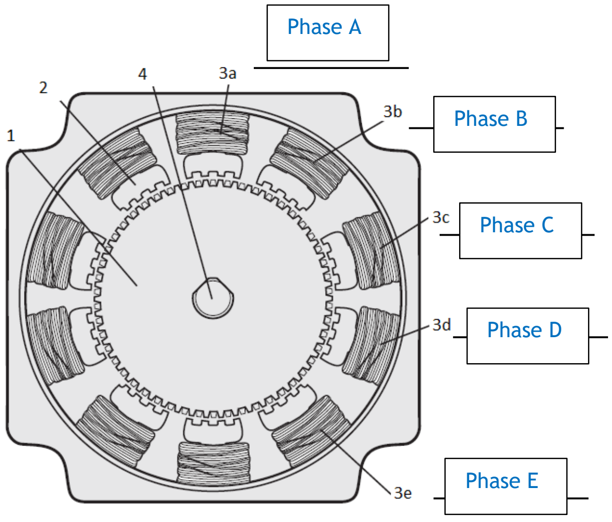


Motor size: NEMA 66,
(approx. 170x162x306), **weight**: **24** kg

4. Identification of the main components of stepper motors

a. Considering the representation below of a stepper motor with 5-phases, identify the components associated by each numbering code.





5. Industrial Stepper Motor Drives

Industrial stepper motor drives are typically **current-controlled, bipolar chopper drives** with microstepping capability. Unlike simple laboratory drivers, industrial drives integrate protection, diagnostics, and communication interfaces suitable for continuous operation in production environments.

Key characteristics include:

- Adjustable phase current and microstepping resolution
- Wide DC bus voltage range to extend the torque-speed envelope
- Protection against overcurrent, overtemperature, and undervoltage
- Industrial interfaces – Drive type (pulse/direction, fieldbus, or integrated controllers)
- Availability of closed loop variants with encoder feedback

Main type of Drives

5.1 Pulse / Direction Interface

The most common command interface used in industrial stepper motor drives.
This interface uses two digital signals, the **pulse (step) and the direction (dir)**

- A digital **STEP** signal commands motion: each pulse corresponds to one motor step or microstep.
- A digital **DIR** signal defines the direction of rotation.
- The motor speed is determined by the **pulse frequency**, while position is given by the **number of pulses** sent.

This interface is typically driven by **PLCs (high-speed outputs), motion controllers, CNC controllers, or microcontrollers**. Motion profiles (acceleration, deceleration, speed ramps) are usually handled by the external controller, while the drive focuses on accurate current-control of the motor phases.

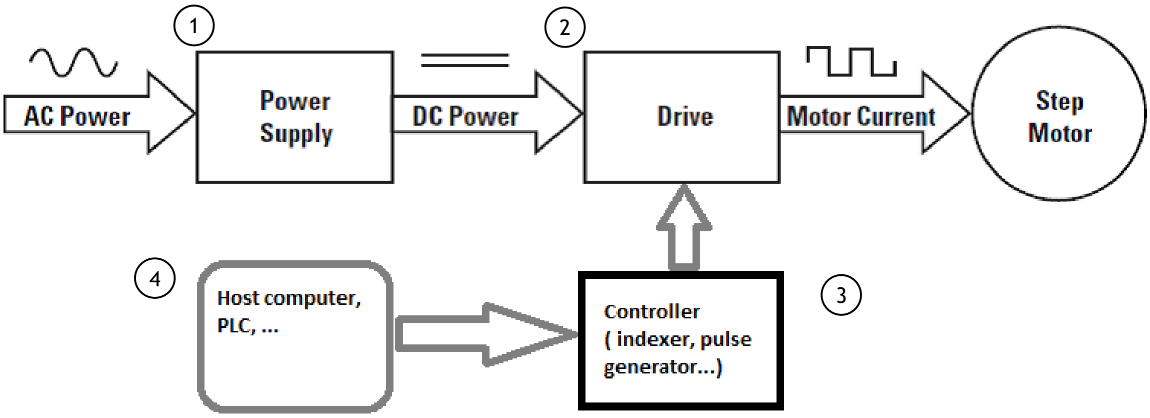
5.2 Fieldbus Interface

The fieldbus interface allows stepper motor drives to be integrated into industrial communication networks, enabling **distributed and coordinated motion control**.
Instead of receiving step pulses, the drive exchanges motion commands and status data with a PLC or motion controller over a digital network such as Modbus, CANopen, EtherCAT, PROFINET, or Ethernet/IP. Motion profiles (position, speed, acceleration) are typically generated and executed inside the drive, while the controller manages high-level coordination.

5.3 **Integrated Controllers (Drive + Controller)**

Integrated controllers combine the **stepper motor drive and motion controller in a single unit**, forming a compact and self-contained motion solution.
In these systems, motion profiles (position, speed, acceleration, dwell time) are stored and executed **inside the drive**, eliminating the need for an external pulse generator or dedicated motion controller. Commands are typically issued via **digital I/O, fieldbus communication, or PC-based configuration software**. This simplifies system design but limits flexibility for complex multi-axis coordination.

a. The following figure represents a possible configuration of the main elements, or functional blocks required to command and control a stepper motor. Justify the need for each element.



(1) Power supply: ___ ___ provide DC power for the driver ________________________________
(2) *Drive*: ____________ power circuit that connects each phase of the motor ______________
(3) Controller (indexer): _ pulse generator signals to command the drive __________________
(4) Host controller: _____ motion commands (i.e. position, velocity, accel., seq. of movements…)

b. Complete the following table based on the offer that Oriental Motor provides

Drive type interface	Oriental Motor: motor series and controller example	Control philosophy
Pulse / Direction	PKP + CVD Series (open loop, pulse Input) αSTEP AR Series + ARD-K (Closed Loop, Pulse Input)	External controller generates pulses
Integrated controller	αSTEP AR Series + ARD (Closed Loop Driver Stored Data Type) PKP Series 5-Phase- CVK-SC Speed control driver	Built-in controller, Motion executed inside drive
Fieldbus/ EtherCAT	αSTEP AZ Series (EtherCAT Compatible Drivers)	Networked, distributed motion

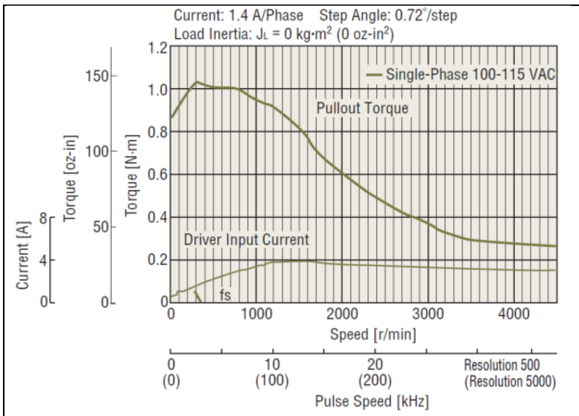
c. Using the information available in the Oriental Motor web site verify what could be the cost for each of these alternative solutions.

Drive type interface	Oriental Motor family	Typical price (USD)	System role
Pulse / Direction	CVD Series	160 - 230	External motion control
Integrated Controller	αSTEP ARD (ARD-K)	420 - 500	Stand-alone motion
Fieldbus / EtherCAT	αSTEP AZD	790	Networked multi-axis

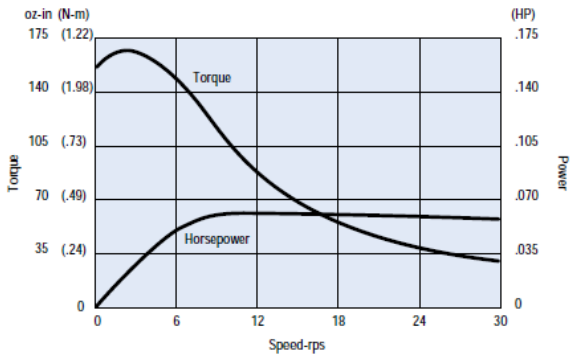
d. What supply voltages are used for Oriental motor drives? Complete the following table

Supply type	Typical values	Internal DC voltage	Industrial use
DC input	24 VDC 48 VDC	24 V 48 V	PLC cabinets, compact machines, mobile systems
AC input	100-120 VAC 200-240 VAC	155 V 325 V	Industrial machinery, high-speed applications

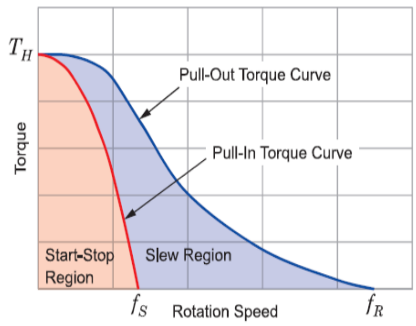
6. Characteristic curves

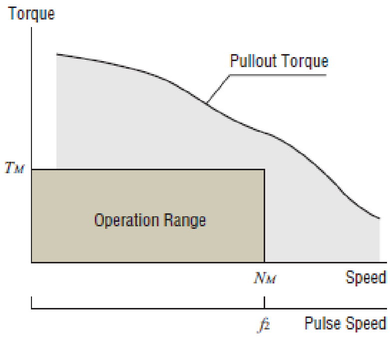


Torque, velocity (ω,T)
[www.orientalmotor.com]



Power, velocity (ω,P)





Operation range
[www.orientalmotor.com]

7. General characteristics of stepper-motors

- Especially suited to fast, repetitive movements in short distances.
- Allow open-loop control, but there are also solutions available based on closed loop control with rotor positioning sensors installed on the motor.
- Low cost motors, highly robust and reliable; low or no maintenance requirements, designed to operate at zero velocity.
- High torque capacity at low speed, favoring direct drive solutions (i.e. avoid the need for a gear transmission).
- Torque varies widely with velocity, which makes the stall torque its main reference characteristic.
- Stall torque: …, 0.23-43.3 Nm, …
- Velocity: up to 3000 rpm, …
- Electrical supply: digital voltage/current signals (i.e. sequence of pulses)

Problems and limitations

- Resonance effects and high stabilization times.
- Irregular operation at low velocity, overcome with a micro-step driver.
- No detection of positioning losses in open-loop control.
- Consume energy even without load, which leads to motors reaching high temperatures.
- Performance deteriorates with increase in velocity.
- Especially noisy at high velocity.
- Limitations on available sizes.

8. Selection and sizing of stepper motors

Rules for Sizing Stepper Motors
Rule 0 — Define the Motion Type First
Before any calculations, classify the application:

- **Rotary** (direct drive, belt, gearbox)
- **Linear** (lead screw, ball screw, rack & pinion)
- **Duty**: positioning, indexing, or continuous motion
- **Speed profile**: start/stop, constant speed, trapezoidal

Rule 1 — Define the Load and Mechanics
1.1 Load inertia

Consider
For rotary motion: $J_{load}^{load} = J_{mass\ J}^{load}$
For linear motion: $J_{load}^{load} = J_{mass\ M}^{load}$

The load includes, apart from the actual payload, couplings, pulleys, screws

Reflect the load inertia to the motor axis:

For rotary motion $J_{load}^{motor} = \frac{J_{load}^{load}}{\eta \cdot i^2}$
where i is the gear reduction ratio and η is the efficiency of the transmission system

For linear motion $\boldsymbol{J_{massM}^{motor}} = \frac{\boldsymbol{m}}{\boldsymbol{\eta}} * \left(\frac{v_{massM}^{load}}{\omega_{motor}}\right)^{\boldsymbol{2}}$
where m is the moving mass, $\boldsymbol{v}$ is the linear speed, $\boldsymbol{\omega}$ is the motor angular speed, and η is the efficiency of the transmission system

---

1.2 Friction and external forces

Determine existing friction forces, external process forces (cutting, pressing, etc.), and gravitational forces (vertical axes)

For linear systems: $F_{total} = F_{friction} + F_{external} \pm F_{gravitical}$

Rule 2 — Define Motion profile and operating speed
Determine the required motion profile and operating speed
Stepper motors cannot start instantaneously at high-speed. Smooth acceleration and deceleration ramps are required, particularly for high-inertia loads

Specify explicitly:

- Maximum speed
- Acceleration (α) or (a)
- Move distance
- Move time
- Resolution required (steps / mm or deg.)

Rule 3 — Calculate Required Torque
3.1 Acceleration torque, T_{acc} (dominant term)

3.2 Static torque, T_{static}

3.3 Total required torque

$$T_{required} = (T_{acc} + T_{static}) \cdot SF$$

Use safety factor SF=1.5 to 2.0 minimum, depending on open-loop/closed-loop control mode

Rule 4 — Evaluate Speed-Torque Curve (Critical Step)
4.1 Determine operating speed
Convert motion to motor RPM

4.2 Check torque at required operating speed
From motor datasheet:

- Extract **available torque at required RPM**
- Must satisfy:

  $T_{motor}(@RPM) \geq T_{required}(@RPM)$

If not → increase motor size, voltage, drive, or gearbox reduction, transmission ratio
Verify the motor standstill torque. Consider the possibility to use a brake

Rule 5 — Inertia Ratio Rule (Very Important)
Stepper motors are sensitive to inertia mismatch.

Proper inertia matching is essential, to maintain stability and dynamic performance. Check recommended values given by the manufacturer of motor/driver

$$Inertia\ Ratio = \frac{J_{load}^{motor}}{J_{motor}}$$

Recommended limits [parker]:

- ≤ 10:1 → Acceptable
- > 10:1 → Risk of stalling or vibrations

Note that in closed-loop control can be acceptable an inertia ratio ≤ 30:1 [ref. alpha motors from orientalmotor.com]
If too high: add gearbox; increase motor size; reduce acceleration

Rule 6 — Choose Step Angle & Resolution
6.1 Base step angle

- 1.8° (200 steps/rev) → standard
- 0.9° (400 steps/rev) → higher resolution, less torque per amp

6.2 Microstepping (rule)

- Improves smoothness; does NOT increase accuracy proportionally; torque per microstep decreases

Max practical microstepping:

- 8–16× for positioning (tipical values in most drives)

Rule 7 — Electrical Sizing (Motor + Driver)

Consider the supply voltage, drive topology, current regulation method, and thermal limits of both driver and motor

7.1 Voltage rule

Stepper torque at speed improves with voltage.
Choose driver voltage 5–10× motor rated voltage (limited by driver rating, motor current and thermal constraints)
The choice of driver supply voltage is motor-dependent, but not tied to the motor's rated voltage as a limit.

7.2 Current rule

- Driver current ≥ motor phase current
- Set correctly to avoid overheating or torque loss

7.3 Inductance check

Lower inductance motors give: higher speed torque; faster current rise
Prefer low inductance, high current motors for speed.
This is why parallel wiring (low inductance) is preferred for speed, while series wiring (high inductance) favors low-speed torque.

Rule 8 — Thermal & Duty Cycle Check

Stepper motors draw current even at standstill. Evaluate duty cycle carefully and use standstill current reduction features, if available, to minimize heating and improve efficiency.

Ensure:

- Motor temperature stays within ratings
- RMS torque ≤ motor continuous torque
- Adequate cooling at standstill (stepper worst-case heating)
- Reduce current during holding or idle states (common in stepper drivers)

If high standstill torque is needed:

- Reduce holding current when idle
- Consider closed-loop stepper

Rule 9 — Verify Stability Margins

Before final selection, confirm:

- Torque margin ≥ 30% at top speed (include now the torque to accelerate the rotor of the chosen motor)
- No mid-band resonance issues
- Acceleration below pull-out curve

Add:

- damping (rubber couplings); acceleration ramps; closed-loop feedback if critical

---

Recommended values from Oriental Motor:

Safety Factor: Sf (Reference value)

Product	Safety Factor (Reference value)
αSTEP	1.5~2
Stepping Motor	2

Inertia Ratio (Reference values)

Product	Motor Frame Size [mm]	Inertia Ratio
αSTEP	28, 42, 60, 85	30 Max.
Stepping Motor	20, 28, 35	5 Max.
	42, 50, 56.4, 60, 85	10 Max.

(http://www.orientalmotor.com)

Exercice

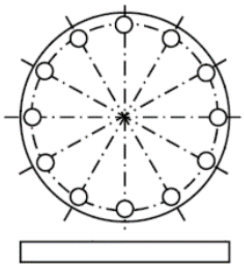
Selection and Justification of a Stepper Motor for an Indexing Table

An indexing table used in an industrial automation system must position parts at equally spaced angular positions with repeatability and reliability. The motion is cyclic, deterministic, and controlled by a PLC.

The objective of this exercise is to **select and justify an appropriate stepper motor and drive solution**, using manufacturer data (Oriental Motor), applying industrial sizing rules.

Given Data

- Number of positions: **12**
- Angular displacement per index: $\Delta\theta = 30°$
- Indexing time: **0.5 s**
- Dwell (holding) time: **1 s**
- Table material: **Aluminum**
    - Density: $\rho = 2660\ kg/m^3$
- Table geometry:
    - Diameter: **160 mm**
    - Thickness: **6 mm**
- Motion quality requirement: **smooth motion (low vibration)**
- Control system: **PLC**, with adjustable indexing parameters



Resolution

Task 1 - Application Analysis

1.1 Choice of motor technology

The application is characterized by:

- Discrete indexing motion (30° steps)
- Repetitive cycles: 12 positions
- Deterministic positioning
- Long dwell time (1 sec) with torque at zero speed: stall torque
- Resolution: *less than 1°… 0.1° …; smooth movement (microstep?)*
- PLC-based control: *PLC connections (?); controller/drive (?); open loop control …*

Stepper motor vs alternatives

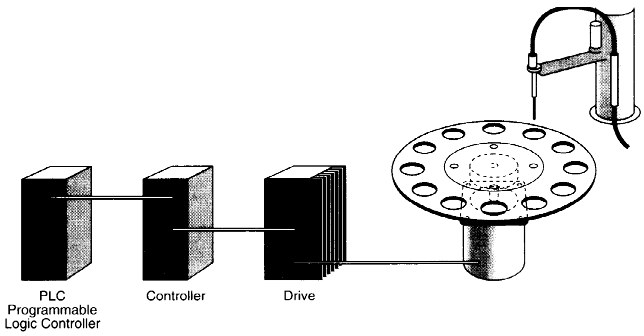
- **DC motor**: requires encoder + control loop → unnecessary complexity
- **AC induction motor**: poor low-speed positioning
- **Servo motor**: technically valid but higher cost and over-dimensioned

Stepper motor is the most appropriate choice

1.2 Stepper motor type

Type	Suitability
VR	Low torque, obsolete
PM	Limited resolution, weak industrial support
Hybrid	High torque, fine resolution, industrial standard

Hybrid stepper motor selected, open loop control



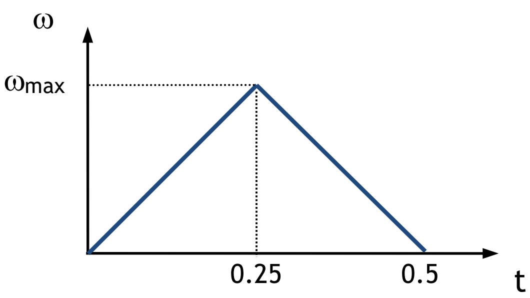
Task 2 - Motion Profile and Speed

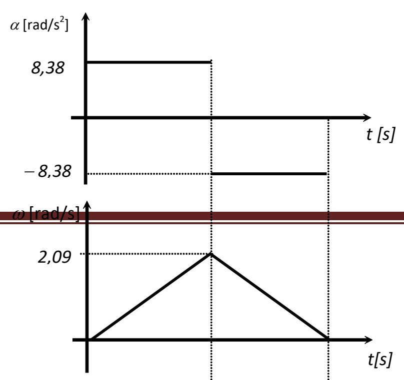
Velocity profile:

i) Controllers for stepper motors normally allow implementation of various movement profiles (i.e. trapezoidal, triangular, sinusoidal …)

ii) Problems of synchronizing the pulse frequency that controls the motor with the resultant motor velocity (start/stop almost instantaneous and acceleration/deceleration profiles).

For this case, a triangular profile was selected:
- short and fast movement
- result in lower values of acceleration/deceleration





$$\begin{cases} \theta = \frac{1}{2}\cdot \alpha \cdot t^2 \\ \omega = \alpha \cdot t \\ \theta = \frac{1}{2}\omega \cdot t \end{cases} \quad \begin{cases} \theta\ (t=0.25) = {}^{\pi}/_{12}\, rad \\ \alpha = 8.38\, rad/s^2 \\ \omega_{máx} = 2.09\, rad/s \cong 20\, rpm \end{cases}$$

Task 3. Load torque

$$T_{acceleration} = T_{acceleration\, Jmotor} + T_{acceleration\, Jcarga} = J_{motor}\cdot \alpha + J_{load}^{motor}\cdot \alpha$$

$$\begin{cases} J_{load}^{motor} = J_{load}^{load} \\ \\ \end{cases} \quad \begin{cases} J_{load}^{motor} = m \cdot \frac{r^2}{2} \\ m = \rho \cdot V \\ V = L \cdot \pi \cdot r^2 \end{cases} \quad \begin{cases} J_{load}^{motor} = m \cdot \frac{r^2}{2} \\ m = 2660 \cdot 1.21 \times 10^{-4} = 0.320\, kg \\ V = 0.006 \cdot 3.14 \cdot \left(\frac{0.160}{2}\right)^2 = 1.21 \times 10^{-4}\, m^3 \end{cases}$$

$$\begin{cases} J_{load}^{motor} = 1.03 \times 10^{-3}\, kgm^2 \\ m = 0.320\, kg \\ V = 1.21 \times 10^{-4}\, m^3 \end{cases}$$

$$T_{acceleration} = J_{load}^{motor} \cdot \alpha = 1.03 \times 10^{-3} \cdot 8{,}38 = 8.61 \times 10^{-3} Nm$$

Note that $T_{acceleration\, Jmotor}$ is not yet known

Task 4. Torque safety margin

Assuming a safety factor of 2.0,

$$T_{motor} = 2 \cdot 8.61 \times 10^{-3} = 1.72 \times 10^{-2} Nm = 17.21\, mNm$$

Task 5. Operating point and inertia matching

Consider **Inertia's ratio: J_{load}/J_{motor} < 10**

$$J_{motor} > \frac{J_{load}}{10} = \frac{1.03 \times 10^{-3}}{10} = 1.03 \times 10^{-4} kgm^2 = 1.03\ kgcm^2$$

Task 6- Motor Selection and Drive

Motor :
Max Speed 20 rpm
$T_{dynamic} > 1.72 \times 10^{-2}$Nm
$J_{motor} \geq 1.03 \times 10^{-4} kgm^2$
Candidate motor (Oriental Motor example)
(60 mm) PKP Series 5-Phase Stepper motor

- Step angle: 0.36°
- Holding torque: 1.25 Nm
- Holding Torque at Motor Standstill: 0.63 Nm
- Rotor inertia: 490×10^{-7} kg·m²

  https://catalog.orientalmotor.com/item/pkp-series-5-phase-stepper-motors/pk-series-60mm-5-phase-stepper-motors/pkp566fmn24b

  Adequate (and large) torque margin and torque at operating speed.

  Holding torque is 73 times greater that the dynamic torque!

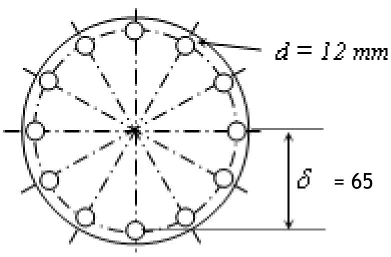
Inertia matching: $\frac{J_{load}}{J_{motor}} = \frac{1.03 \times 10^{-3}}{490 \text{x} 10-7} = 20.1$

this exceeds the ideal limit (≤ 10), but:

- Low speed
- Short movement
- Smooth profile

Alternatively, gear reduction could be added (not required here).

Note that the existing holes in the table were not taken into account in the previous calculation of the inertia of the table. If they were considered:



$$\begin{cases} J_{hole}^{axis\ hole} = m_{hole} \cdot \frac{r_{hole}^2}{2} \\ J_{hole}^{axis\ table} = J_{hole}^{axis\ hole} + m_{hole} \cdot \partial^2 \\ J_{with\ holes}^{axis\ hole} = J_{without\ holes}^{axis\ table} - 12 \cdot J_{hole}^{axis\ table} \end{cases}$$

$$J_{with\ holes}^{axis\ table} = 1.03 \times 10^{-3} - 9.19051 \times 10^{-5} = 9.35 \times 10^{-4}\ kg \cdot m^2$$

The new value for the inertia ratio becomes: 19
NOTE: Oriental Motor for their Alpha series steppers motors, (under closed loop control) refers to inertia ratio of up to 30.

Verification of acceleration torque

Concerning the verification of whether the motor torque available for acceleration can accelerate the load and the motor's inertias, the calculations are as presented below. However, as the inertia´s condition result in a selected motor clearly oversized, in relation to required torque, that would certainly revealed unnecessary, in this case.

$$T_{acceleration} = T_{acceleration\ Jmotor} + T_{acceleration\ Jcarga} = J_{motor} \cdot \alpha + J_{load}^{motor} \cdot \alpha$$

$$T_{acceleration} = 490\ x\ 10^{-7} \cdot 8{,}38 + 1.03 \times 10^{-3} \cdot 8{,}38 = 0.411 \times 10^{-4} + 8.61 \times 10^{-3} = 9.02 \times 10^{-3}\ Nm$$

$$T_{motor} > 2 \cdot 9.02 \times 10^{-3} = 0{,}018\ \text{Nm}$$

Drive type

Current-controlled, bipolar chopper drives **with microstepping capability, open loop control**

Option	Suitability
Pulse/Direction	Simple, PLC compatible
Integrated controller	Overkill
Fieldbus	Unnecessary

Pulse/Direction drive selected

Supply voltage and microstepping

- Supply: 48 VDC (or AC-input drive)
- Microstepping: 8–16 µsteps/step

Benefits: Reduced vibration; faster settling; smoother motion

Microstepping improves smoothness, not absolute accuracy.

Final comment: the application requires low dynamic torque and operates at low speed. The holding torque is important and the choice provides a safety margin. The inertia ratio ends up being less relevant.

Final Selection Summary

Item	Selected solution
Motor /Driver	Hybrid stepper motor pkp566fmn24b, Diver CVK566FAK
Frame size	60 mm
Step angle	0.36
Holding torque	1.25 Nm
Drive type	Pulse / Direction
Supply voltage	48 VDC
Control	PLC (high-speed outputs)
Microstepping	8-16 µsteps/step