DEMec - Dep. of Mechanical Engineering
SAIC- Automation, Instrumentation and Control Section
Master in Mechanical Engineering

Electromechanical Systems

1st Year– 2nd Semester
2025-2026

Support documents to TP classes

Stepper motors

Paulo Abreu

2026 Edition

Stepper motors

Paulo Abreu

March 2026

1

Stepper motors

Paulo Abreu ®

2

U.PORTO
FEUP FACULDADE DE ENGENHARIA
UNIVERSIDADE DO PORTO

Electric Motors classification
Working principle/source of energy

- **Electric motors**
  - **Brushed Motors (*de escovas*)**
    - DC motors
    - AC motors
    - Universal motor
  - **Synchronous Motors (*síncronos*)**
    - Single-phase motors
      - Permanent magnets
      - Reluctance
      - Hysteresis motors
    - Three-phase motors
    - BLDC motors (brushless DC motors)
    - Stepper motors
  - **Asynchronous Motors (*assíncronos*)**
    - Single-phase motors
      - Shadow poles
      - Capacitor start induction motors
    - Three-phase AC induction motors

3

U.PORTO
FEUP FACULDADE DE ENGENHARIA
UNIVERSIDADE DO PORTO

Stepper motors
Introduction

Core Characteristics

The stepper motor is a specialized category of **polyphase synchronous motor** designed to convert digital pulse sequences into precise mechanical incremental displacements. Unlike conventional motors that rely on continuous voltage for rotation, the stepper motor operates as a discrete actuator

- **Electromechanical Construction**
  - **Stator**: comprises **multiple phases** with concentrated windings, typically excited by a DC source through a **Driver**
  - **Rotor**: passive or active magnetic structure (**Variable Reluctance, Permanent Magnet, or Hybrid, …**) that does not require brushes or windings, minimizing maintenance and mechanical complexity
  - **Open-Loop Positioning:** a primary feature is its ability to operate **without a position sensor** (encoder/resolver). Because the rotor aligns with the magnetic field of the stator, position is inherently tracked by counting the number of input pulses
  - **Discrete Kinematics:** The motor translates electrical pulses (N) into a specific angular displacement (θ)

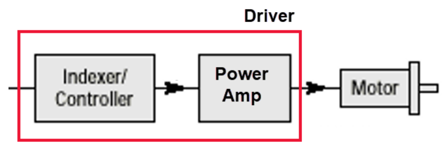
Paulo Abreu ®

4

U.PORTO
FEUP FACULDADE DE ENGENHARIA UNIVERSIDADE DO PORTO

Stepper motors

Working principle



- A synchronous motor variant, but with **time switching commutation**, DC supply, sensorless
- Conversion of electrical impulses into angular motion (inherently digital operation)

one impulse ➔ one step

n impulses ➔ n steps

- Number of impulses ➔ position
- Impulses frequency ➔ speed

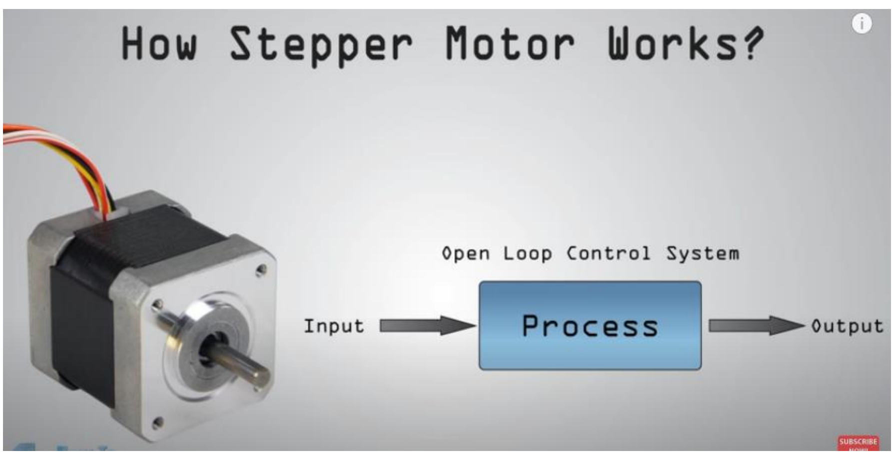
Note: closed loop control (requiring rotor position sensor) can also be used with stepper motors!

Paulo Abreu ®

5

U.PORTO
FEUP FACULDADE DE ENGENHARIA UNIVERSIDADE DO PORTO

Stepper motors



https://youtu.be/TWMai3oirnM?t=10

6

Stepper motors
Advantages

1. High Torque Density at Low Angular Velocity

Unlike induction or DC brushed motors, which often require high RPM to generate significant power, stepper motors provide maximum torque at stall or very low speeds.

- **Physical Basis:** the high pole count (typically 50 or more in hybrid motors) allows for a high magnetic flux density at small displacements
- **Direct Drive Capability:** this high low-speed torque often eliminates the need for mechanical gearboxes, reducing system backlash, mechanical wear, and overall footprint

Paulo Abreu ®

Stepper motors
Advantages

2. Inherent Digital-to-Analog Transduction

The stepper motor acts as a physical bridge between digital control logic and mechanical motion.

- **Quantized Motion**: each pulse corresponds to a discrete angular increment (α). This makes the system "inherently digital," simplifying the interface with microcontrollers and PLCs (e.g., Beckhoff's PLCopen blocks)
- **Mathematical Precision**: the theoretical position (θ) is simply the product of the step count (n) and the step angle (α)

$$\theta_{th} = n \cdot$$

Paulo Abreu ®

Stepper motors
Advantages

3. Open-Loop Positional Reliability

One of the most significant economic advantages is the ability to achieve precise positioning without a feedback sensor (encoder or resolver).

- **Synchronization**: as long as the load torque (T_L) remains below the motor's Pull-out Torque (T_{po}), the motor remains in synchronism with the command pulses
- **Cost Efficiency**: while the electronics (driver) add to the initial BOM (Bill of Materials), the lack of a high-resolution encoder and complex PID tuning algorithms reduces the total system complexity and cost for many applications

Paulo Abreu ®

9

Stepper motors
Advantages

4. Versatile Power Scaling

The technology is highly scalable, ranging from miniature medical pumps to industrial automation.

- **Power Range**: approximately 2 W to 2 kW
- **Holding Torque**: at zero speed, with the windings energized, the motor provides a significant "Holding Torque," which can act as a static brake to maintain position against external forces

5. Maintenance and Robustness

- **Brushless Construction**: because there are no mechanical commutators or brushes (unlike DC motors), the primary wear components are the bearings. This leads to a high Mean Time Between Failure (MTBF)

Paulo Abreu ®

10

Stepper motors Limitations

1. Mechanical Resonance and Instability

Stepper motors are second-order systems that exhibit a natural frequency (f_n). When the input pulse frequency matches this natural frequency, the motor experiences resonance, leading to significant vibration, noise, and potential loss of synchronism

- **Oscillatory Response**: because each step is a discrete move-and-stop command, the rotor behaves like a mass-spring system. After a step, it oscillates around the new equilibrium point before settling
- **Settling Time**: in high-precision applications, the time required for these oscillations to decay (stabilization time) limits the effective throughput of the system

Paulo Abreu ®

11

Stepper motors Limitations

2. Thermal Inefficiency and Constant Current Drive

Unlike Servo motors, which draw current proportional to the load torque (I T), standard stepper drivers typically maintain a constant current ($Imax$) in the windings to ensure holding torque

- **Joule Heating** ($P_{loss} = I^2 \cdot R$): since the motor draws full current even at a standstill or with zero load, it operates at high temperatures
- **Efficiency**: this results in low energy efficiency compared to closed-loop systems, often requiring heat sinks or active cooling in continuous-duty cycles

Paulo Abreu ®

12

Stepper motors
Limitations

3. Loss of Synchronism (Stalling)

In open-loop control, the controller "assumes" the motor has completed a step. If the load torque (T_L) exceeds the motor's Pull-out Torque (T_{PO}), the rotor falls out of phase with the stator's magnetic field

- **Missing Steps**: this leads to cumulative positional errors that the controller cannot detect without a feedback sensor (encoder/resolver)
- **Torque-Speed Limitation**: the inductive reactance ($X_L = 2 \cdot \pi \cdot f \cdot L$) increases with speed, causing the current - and thus the torque - to drop sharply as velocity increases. This restricts stepper motors to low-to-medium speed applications

Stepper motors
Limitations

4. Acoustic Noise and Vibration

The discrete nature of the "step" excitation creates high-frequency harmonics. Without advanced microstepping or damping, this leads to:

- **Audible Noise**: vibration transmitted through the machine frame
- **Surface Finish Issues**: in CNC applications, raw full-stepping can leave visible "steps" or patterns on a finished part

U.PORTO FEUP FACULDADE DE ENGENHARIA UNIVERSIDADE DO PORTO

Stepper motors Classification

The three primary types of stepper motors are distinguished by their **rotor construction**, which dictates their step resolution, torque density, and "detent" behavior

1. **Permanent Magnet (PM) - "Can-Stack" Motors**
   - The rotor consists of a permanent magnet with multiple alternating North and South poles
2. **Variable Reluctance (VR)**
   - The rotor is a "passive" element made of soft magnetic material (laminated steel) with teeth, but no magnets
3. **Hybrid (HB) The Industrial Standard**
   - The hybrid motor combines the features of both PM and VR motors. It features a permanent magnet axial core with two toothed "end-caps" (cups) made of soft iron

15

Paulo Abreu ®

U.PORTO FEUP FACULDADE DE ENGENHARIA UNIVERSIDADE DO PORTO

Permanent Magnet (PM) – "Can-Stack" Motors

Main elements
- Rotor: permanent magnet (multi-pole)
- Stator: a set of DC-powered polar windings

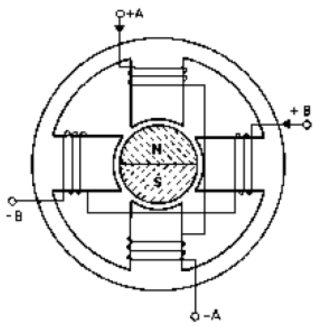
Operating Principle
- Interaction between the stator's electromagnetic field and the rotor's permanent magnetic field (Lorentz force)
- Time switching in driving the stator windings (driver required)

Characteristics
- Large Step Angle: typically 7.5° to 18° (48-20 steps/rev).
- High Detent Torque: high residual torque when unenergized (does not run freely)
- Low Cost: often used in non-precision consumer goods (printers, scanners)
- Limited maximum speeds
- High rotor inertia

https://www.portescap.com/en/products/stepper-motors/can-stack-motors

16

Permanent Magnet (PM) – "Can-Stack" Motors



Simplified version
Motor with 2 phases, 2 pairs of poles

$\alpha = p_e / N_r$

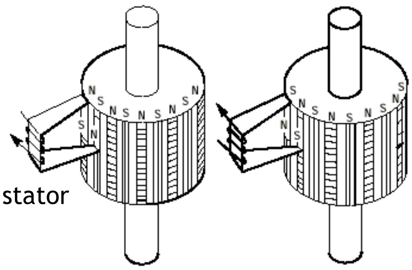
α - step angle

p_e – stator angular step

=360°/number pairs of poles in the stator

N_r - n° of pairs of poles in the rotor

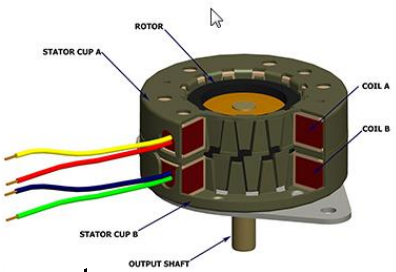
Simulation from en.nanotec.com



https://www.portescap.com/en/products/stepper-motors/understanding-can-stack-motors

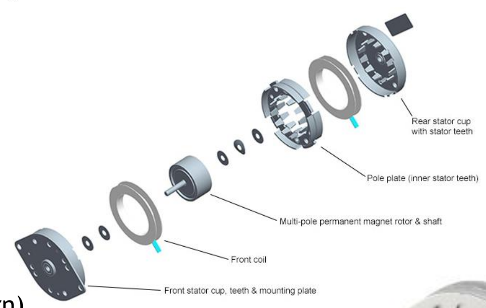
17

Permanent Magnet (PM) – "Can-Stack" Motors



- **2-phase motors**
  - Step angle from 3.6° to 18° (100 to 20 steps per turn)
  - 4 or 6-wire configuration

- Example: 2-phase motor, with 12 pole pairs in each stator winding, 2 pole pairs in the rotor, provides 48 steps per revolution (7.5° per step)
  $\alpha = p_e / N_r = (360°/24) / 2 = 7.5°$



www.portescap.com/

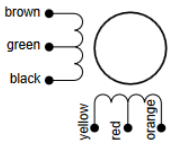
Motor 20M020D (approx. diam 20 mm, 11 mNm)

18

Permanent Magnet (PM) – "Can-Stack" Motors

Motor Portescap 20M020D (Approx. diam 20 mm, 11 mNm)

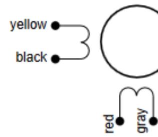
Electrical Data	20M020D•• 1U Unipolar	2U Unipolar	1B Bipolar	2B Bipolar	Unit
1 Operating Voltage	5	12	5	12	VDC
2 Resistance per Phase, ± 10%	20.0	115.2	20.0	115.2	Ohms
3 Inductance per Phase, typ	3.9	20.3	7.8	52.8	mH
4 Rated Current per Phase *	0.25	0.10	0.25	0.10	A
Coil Independent Parameters					
5 Holding Torque, MIN *	7.8 (1.11)	7.8 (1.11)	11.0 (1.56)	11.0 (1.56)	mNm (oz-in)
6 Detent Torque, Max	3.53 (0.5)				mNm (oz-in)
7 Rotor Inertia	0.41 (0.00224)				gcm² (oz-in²)
8 Step Angle	18.0				Degree



UNIPOLAR COIL

YELLOW	ORANGE	BROWN	BLACK	RED/GREEN
+	-	+	-	+
+	-	-	+	+
-	+	-	+	+
-	+	+	-	+
+	-	+	-	+

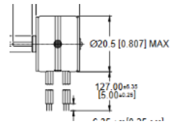
CW ↓ / CCW ↑
VIEWED FROM OUTPUT SHAFT



BIPOLAR COIL

RED	GRAY	YELLOW	BLACK
+	-	+	-
+	-	-	+
-	+	-	+
-	+	+	-
+	-	+	-

CW ↓ / CCW ↑
VIEWED FROM OUTPUT SHAFT



Portescap 20M020D

Variable Reluctance (VR) Motors

Main elements

- Rotor: soft iron rotor, non-magnetic, with “teeth” and “grooves”
- Stator: configured as a 3-phase, or 4-phase, or 5-phase set of DC-powered polar windings

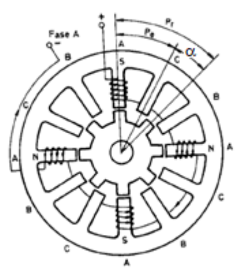
Operating Principle

- The rotor moves to the position that minimizes the magnetic reluctance of the circuit.
- Time switching in driving the stator windings (driver required)
- Torque (T) is proportional to the square of the current (i) and the change in inductance (L) relative to position (θ): $T = 1/2\ i^2\ (\frac{dL}{d\theta})$

Characteristics

- No Detent Torque: the rotor spins freely when the power is off
- High Step Rate: low rotor inertia allows for high acceleration
- Low dampening characteristics of oscillations
- Lower torque/size ratio compared to other motor types

α - step angle
p_r - rotor angular step
p_e - stator angular step
$\alpha = |\ p_r - p_e\ |$



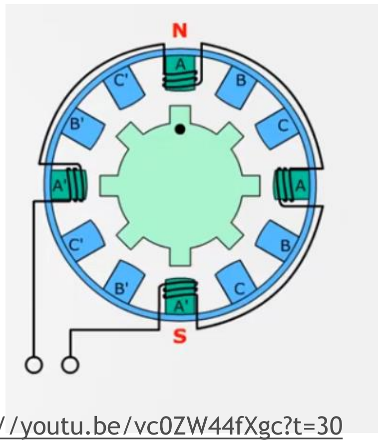
Example of a 3-phase motor, with 12 “teeth” on the stator and 8 on the rotor, 15º pitch (α = |360º/12 - 360º/8| = 15º)

Paulo Abreu ®

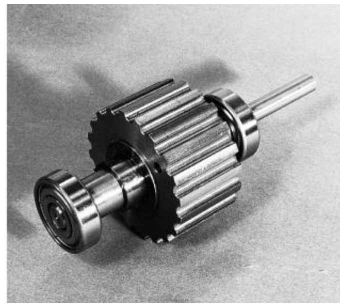
Variable Reluctance (VR) Motors

Operating Principle

VR stepper motor, with 3-phases, 12 "**teeth**" on stator
8 "**teeth**" on rotor
Step angle α = 15°
(24 steps per turn)



https://youtu.be/vc0ZW44fXgc?t=30



Soft-steel rotor with finely notched teeth in a VR stepper motor

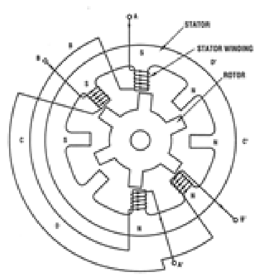
Ref. Nidec.com

21

Variable Reluctance (VR) Motors

- Multiple configurations
- Motors with 3-phase, 4-phase, or 5-phase
- No detent torque
- Problems with high inertial loads

Common VR motors Step angle	Number of steps per turn
1.8°	200
5°	72
7.5°	48
15°	24



4 phase VR motor with two phases on.

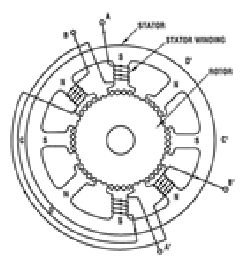


Diagram of 1.8° VR motor.

Ref. applied_motion.com

22

U.PORTO FEUP FACULDADE DE ENGENHARIA UNIVERSIDADE DO PORTO

Hybrid (HB) Motors

Main elements

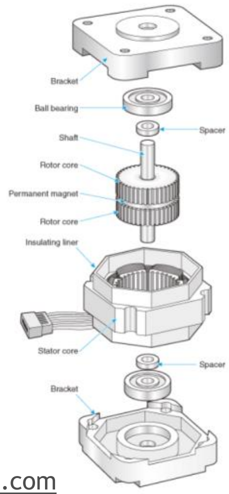
- Rotor: permanent magnet combined with teeth, like the VR motor
- Stator: a set of DC-powered polar windings

Operating Principle

- It utilizes both alignment torque (from the magnet) and reluctance torque (from the teeth)
- Time switching in driving the stator windings (driver required)

Characteristics

- High Resolution: small step angles, typically 1.8º (200 steps per turn), or 0.9º
- High Torque Density: the most powerful type for its size
- Static Stability: strong holding torque and moderate detent torque
- Can operate at high speeds



Ref. Nidec.com

U.PORTO FEUP FACULDADE DE ENGENHARIA UNIVERSIDADE DO PORTO

Hybrid (HB) Motors

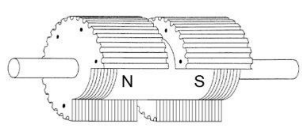
Typical configuration

- Motor with two phases
- Stator with 8 poles, with 6 “teeth” each, (in total of 48 “teeth”)
- Rotor with two sections with 50 “teeth” each
- Step angle (α) of 1.8º (200 steps per turn)

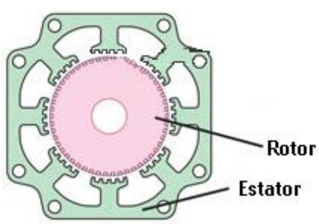
Other configurations

- Step angle of 0.9º, or 3.6º (400 or 100 steps per turn)

Videos:
Nanotec
https://youtu.be/eyqwLiowZiU?t=155



Hybrid Stepper Motor Rotor



Nº steps (S_{rev}) = nº rotor teeth (Z_r)* nº phases (m) = (2 * 50) * 2 = 200

Stepper motors
Terminology and concepts

1. Structural Parameters (The Motor Architecture)

- **Phase (m):** the number of independent windings on the stator.
  Most industrial motors are 2-phase, though 3-phase and 5-phase variants exist for higher smoothness
- **Poles**
  Related to the number of electromagnetic poles (pairs of north and south poles), either in the stator or in the rotor; the poles are generated either by a permanent magnet or a coil (through an electrical current)
- **Step Angle (α):** the angular displacement of the rotor for each input pulse.
  Steps per turn (S_{rev}): the number of steps required for one full 360º revolution

$$S_{rev} = \frac{360}{\alpha}$$

25

Paulo Abreu ®

Stepper motors
Terminology and concepts

2. Static Torque Characteristics (At Standstill)

These concepts describe the motor's ability to maintain position or resist external forces.

- **Holding Torque** (T_H): the maximum torque the motor can resist while energized at a standstill without losing its equilibrium position. This is the primary rating used in motor datasheets
- **Detent Torque** (T_D): the torque required to rotate the motor when the windings are not energized. This is caused by the permanent magnets' attraction to the stator teeth (only present in PM and Hybrid types)

26

Paulo Abreu ®

U.PORTO
FEUP FACULDADE DE ENGENHARIA UNIVERSIDADE DO PORTO

Stepper motors
Terminology and concepts

3. Dynamic Performance (In Motion)

These terms define how the motor behaves when pulses are applied at frequency (f).

- **Pull-in Torque**: the maximum torque at which a motor can start, stop, or reverse instantaneously without losing steps
- **Pull-out Torque**: the maximum torque a motor can provide at a constant speed before "stalling" (falling out of synchronism)
- **Slew Range**: the high-speed region where the motor can operate but cannot start or stop abruptly without a ramp (acceleration/deceleration)
- **Start/Stop Rate**: the maximum pulse frequency at which an unloaded motor can start and stop without losing steps

Paulo Abreu ®

U.PORTO
FEUP FACULDADE DE ENGENHARIA UNIVERSIDADE DO PORTO

Stepper motors
Torque-speed curve

14. Slew range: operating area but a motor can not be started directly in the slew range. After starting the motor somewhere in the self-start range, the motor can be accelerated into or load applied into the slew range. The motor must then be decelerated or load reduced back into the self start range before the motor can be stopped

8. Maximum No-load starting speed

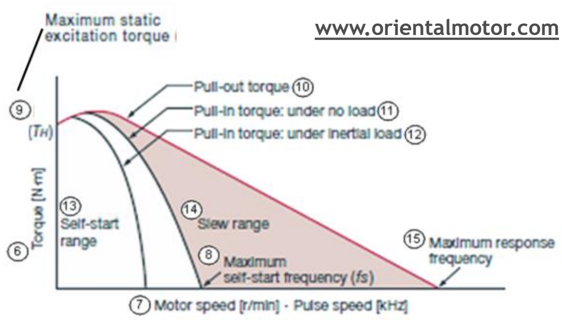
9. Holding Torque

10. Pull-out Torque curve

11. Pull-in Torque curve (no load)

12. Pull-in Torque curve (inertial load): the maximum torque and speed combination that a motor with an inertial load (i.e. damper) can supply to a load and start or stop without any acceleration or deceleration. In order to operate above the pull-in torque curve, the motor must be accelerated into or decelerated out of the slew range.

13. Self start range (start/stop region): the motor can start, stop or change directions in synchronism without the need for acceleration or deceleration



Stepper motors
Terminology and concepts

4. Control Concepts (The Drive Logic)

Terms related to how the power electronics interact with the motor

Full-Step vs. Half-Step

- Full-Step: one-phase or two-phases energized to achieve the rated α
- Half-Step: alternating between one and two-phases to achieve $\alpha/2$ resolution

Microstepping (n)

- A technique where the driver controls the current in each phase sinusoidally to create "virtual" steps between the physical teeth ($\theta_{micro} = \alpha / n$ with n as the microstep divisor)
- Reduces resonance and increases positioning resolution to as high as 256 microsteps per full step

L/R Drive vs. Chopper Drive

- **Chopper Drive (PWM/Constant Current):** uses high-voltage pulses and Pulse Width Modulation (PWM) to force current into the inductive windings quickly, maintaining torque at higher speeds
- **L/R Drive (Constant Voltage):** it applies a fixed voltage directly to the motor phases

Paulo Abreu ®

29

Stepper motors
Terminology and concepts

Term	Symbol	Unit	Engineering Significance
Step Angle	α	Degrees (º)	Defines positional resolution
Steps per turn	S_{rev}		Number of steps per rotation $S_{rev} = 360º/\alpha$
Inductance	L	mH	Limits the rate of current rise ($\frac{di}{dt}$), affecting high-speed torque
Pulse Frequency	f	Hz (Steps/sec)	Directly determines angular velocity ω
Rotor Inertia	J	kg· m^2	Affects acceleration and resonance frequency

30

Stepper motors
Terminology and concepts

Winding Topologies and Wiring Configurations

1. **Phase vs. Winding Configuration**

While most industrial stepper motors are 2-phase (Phase A and Phase B), they can be wired as either **Unipolar** or **Bipolar**. This choice impacts the power electronics required

- **Unipolar Configuration**
  In a unipolar setup, each phase has a center tap. Current always flows in the same direction through each half-winding.
  - **Wiring**: typically 5 or 6 wires
  - **Operating Principle**: to reverse the magnetic field, the driver simply switches which half of the coil is energized
  - **Advantage**: simplifies the driver (only 4 simple switches/transistors are needed)

Paulo Abreu ®

31

Stepper motors
Terminology and concepts

Winding Topologies and Wiring Configurations

1. **Phase vs. Winding Configuration**

- **Bipolar Configuration**
  In a bipolar setup (two-phase motor) the entire winding is used, and the driver must be able to reverse the current flow through the phase.
  - **Wiring**: typically 4 or 8 wires
  - **Operating Principle**: requires an H-Bridge circuit to push current in both directions (+I and -I)
  - **Advantage**: higher torque at low speeds and better efficiency

Paulo Abreu ®

32

Stepper motors
Terminology and concepts

Wire Count and Connection Logic in Two-phase Stepper Motors

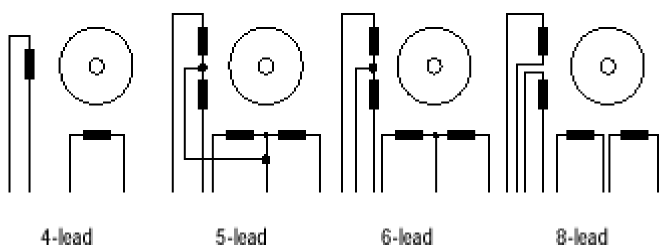
Wire Count	Type	Engineering Flexibility
4 Wires	Bipolar	Simplest to connect; phases are strictly independent.
5 Wires	Unipolar	Center taps are tied together internally to a single common wire.
6 Wires	Universal (unipolar/bipolar)	Two separate center taps. Can be used as Unipolar or Bipolar (leaving center taps floating).
8 Wires	Universal (unipolar/bipolar)	All 4 coil ends are accessible. Allows for Series or Parallel bipolar connection.

33

Stepper motors
Terminology and concepts

Wire Count and in Two-phase stepper motors

- one winding per stator pole ➔ 4 wires
- two windings per stator pole➔ 5, 6 or 8 wires



Common configuration:
8-wire, two windings per stator pole, allowing series or parallel connection

Paulo Abreu ®

34

U.PORTO FEUP FACULDADE DE ENGENHARIA UNIVERSIDADE DO PORTO

Stepper motors
Terminology and concepts

Series vs. Parallel (in two-phase, 8-Wire Motors)

- **Series Connection**
  - **Inductance** (L): increases ($L_{total} = 4 \times Lcoil$)
  - **Result:** high torque at low speeds, but torque drops rapidly at high speeds due to high inductive reactance ($X_L = 2 \cdot f \cdot L$)

- **Parallel Connection**
  - **Inductance (L):** decreases (**$L_{total} = Lcoil$**)
  - **Result:** lower inductive reactance allows current to rise faster (di/dt), maintaining torque at much higher speeds

Paulo Abreu ®

35

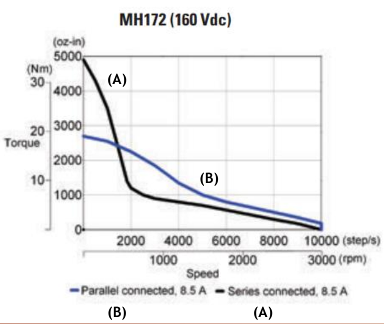
U.PORTO FEUP FACULDADE DE ENGENHARIA UNIVERSIDADE DO PORTO

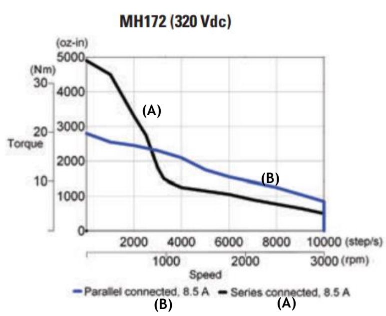
Stepper motors

Torque-Speed Curve in Two-Phase, 8-Wire Stepper Motors: Series vs. Parallel Configuration

Kollmorgen MH172 Series High-Torque Stepper Motors

- Hybrid stepper motor, 2-phase, 8-wire, 200 steps per revolution



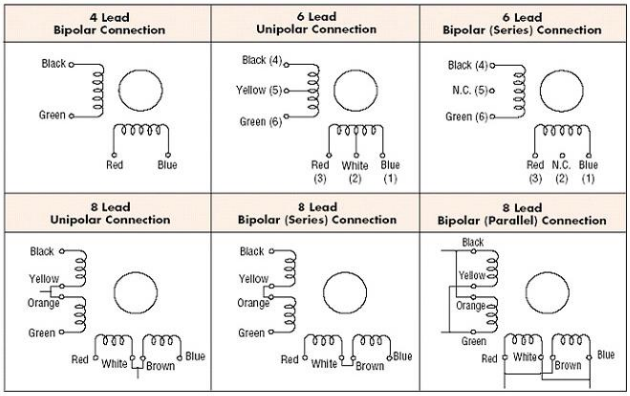


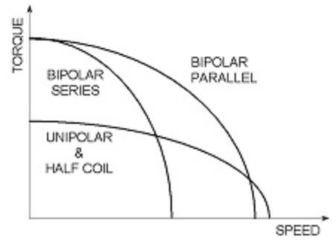
Note: difference on torque/speed from using 160 V DC versus 320 V DC

36

Stepper motors
Two-phase motors

Motors, wires and driver (unipolar/bipolar)





Note: torque-speed curves dependent on driver and motor configuration

https://www.orientalmotor.com/stepper-motors/technology/unipolar-bipolar-connections.html

37 Paulo Abreu ®

Stepper motors
Five-phase motors

While 2-phase stepper motors are the industrial standard, **5-phase stepper motors** are utilized in high-precision applications where vibration damping and high resolution are critical

Physical Construction and Step Angle

- A 5-phase motor has 10 stator poles (2 poles per phase)
  Because the phases are offset by smaller geometric increments, the native resolution is significantly higher.
  - For a 2-phase motor $(m = 2, Z_r = 100)$: $\alpha = \frac{360º}{m \cdot Z_r} = \frac{360º}{200} = 1.8º$
  - For a 5-phase motor $(m = 5, Z_r = 100)$: $\alpha = \frac{360º}{m \cdot Zr} = \frac{360º}{500} = 0.72º$

  This means a 5-phase motor provides 500 full steps per revolution without the need for microstepping

38 Paulo Abreu ®

Stepper motors
Five-phase motors

Reduced Torque Ripple and Vibration

In a stepper motor, torque is not perfectly constant; it pulsates as the rotor moves from one equilibrium point to the next

- **2-phase motors**: the "valleys" between torque peaks are deep, which can trigger mechanical resonance at low speeds. Ripple has a higher magnitude and lower frequency
- **5-phase motors**: because there are more phases overlapping, the torque "valleys" are much shallower, and as a result, the Ripple is lower. This results in a significant reduction in audible noise, virtually no resonance at low speeds, allowing to have a smoother motion profile

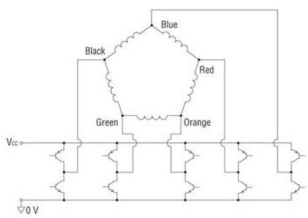
39

Paulo Abreu ®

Stepper motors
Five-phase motors

Winding Configurations: The Pentagon Connection Used in 5-Phase Stepper Motors

- Standard 5-Phase has 10 wires (2 per phase), which is complex to wire
- With a Pentagon Connection, the phases are internally connected in a closed loop (like a pentagon). This requires only 5 leads to the driver
- This configuration allows the driver to energize 4 or 5 phases simultaneously, providing a more stable magnetic field vector



Note: The driver for a 5-phase motor differs fundamentally from a 2-phase motor driver, which typically uses an H-bridge architecture!

40

Paulo Abreu ®

Stepper motors
Two-phase motor versus Five-phase motor

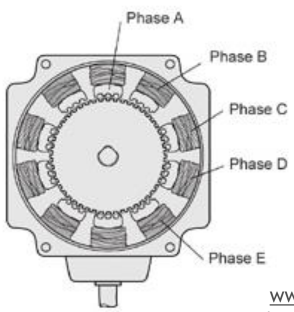
Feature	2-Phase Motor	5-Phase Motor
Standard Step Angle	1.8º	0.72º
Steps per Revolution	200	500
Vibration/Resonance	High (requires microstepping)	Very Low (inherently smooth)
Torque at High Speed	Moderate	Excellent (less torque drop-off)
System Cost	Lower (standardized)	Higher (specialized driver needed)

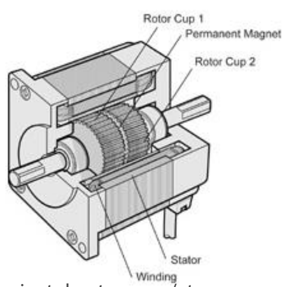
41

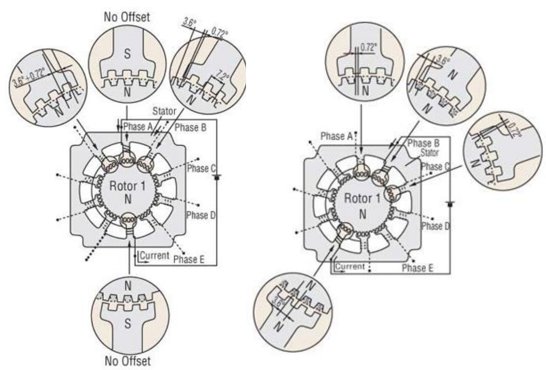
Stepper motors
Five-phase Hybrid (HB)

Hybrid step motor with 5-phases, from oriental motor (www.orientalmotor.com)

- Stator with 5 phases, 10 poles (400 teeth)
- Rotor with two sections, 50 teeth each, with misalignment of 3.6°, and permanent magnets
- Step angle of 0.72°, (500 steps per turn)







www.orientalmotor.com/stepper-motors/technology/stepper-motor-overview.html

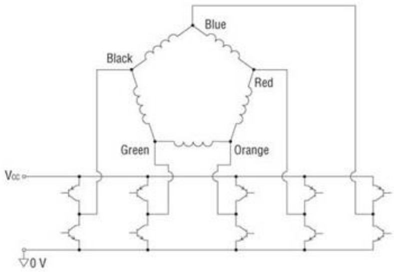
42

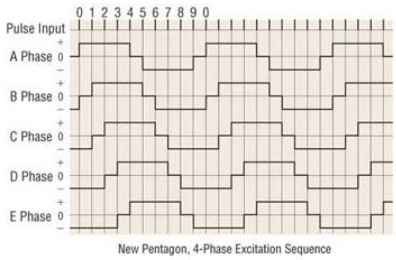
Stepper motors
Five-phase Hybrid (HB)

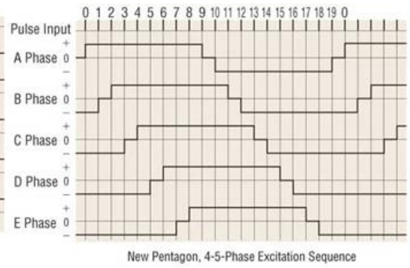
Hybrid step motor with 5 phases, from Orientalmotor

- with driver Pentagon, 4-phase Excitation: Full Step System (step angle of 0.72˚)
- with driver Pentagon 4-5-phase Excitation: Half-Step System (step angle of 0.36˚)

(angular step =360º/ (50 teeth*2)*5 phase = 0.72º)

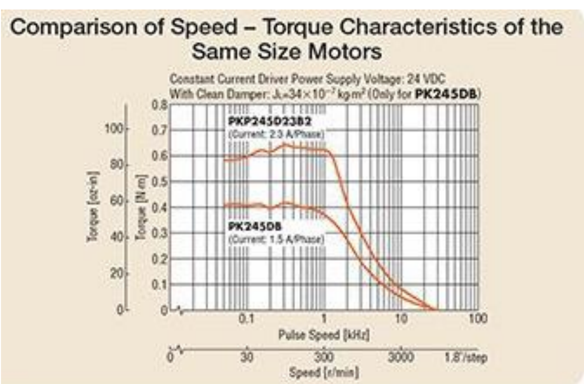


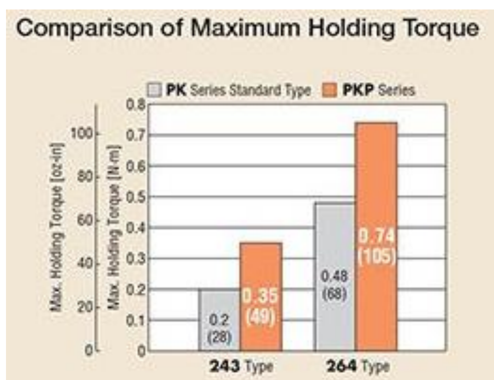




43 www.orientalmotor.com/stepper-motors/technology/stepper-motor-overview.html

PKP Series 2-Phase (HB) Bipolar Stepper Motors from Orientalmotor





44 https://www.orientalmotor.com/stepper-motors/2-phase-stepper-motors-pkp-series.html

Paulo Abreu ®

RKII Series 5-Phase (HB) Stepper Motors from Orientalmotor

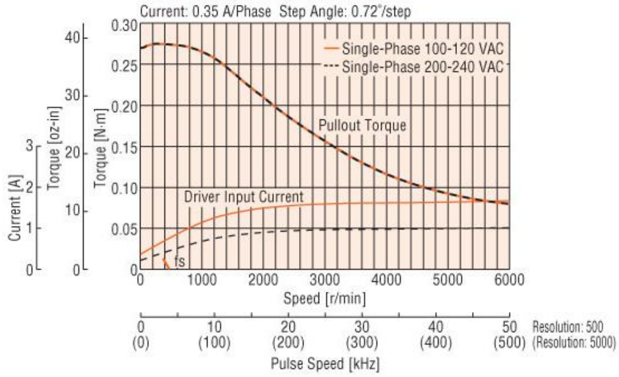
Torque-speed curve

- Dependent on the driver, and motor
- For use with RKII Series AC Input Drive
- Hybrid Stepper Motor
- Step angle: 0.72° (500 steps per turn)
- Driver with microstep control

Note: motor driver powered by single-phase 110 VAC or 230 VAC has impact on driver input current!

https://catalog.orientalmotor.com/item/tegories-shop-online-stepper-motor-driver-packages/r-motor-driver-packages-pulse-input-type-no-cables/rks545aa?ss360SearchTerm=rks545

RKS545



Paulo Abreu ®

Stepper Motor Drivers

1. Introduction

Stepper motors require an **electronic driver** to convert high-level motion commands into controlled current waveforms for the motor windings. Modern stepper drivers range from simple open-loop pulse interfaces to advanced vector-controlled closed-loop systems capable of servo-class performance.

A typical driver consists of two main functional blocks

A. Indexer (Control Stage)

- Interprets high-level commands (e.g., step/direction, fieldbus, or serial communication)
- Generates reference trajectories (position, speed, acceleration)
- Manages step modes (full-step, half-step, microstep)

B. Power Amplifier (Power Stage)

- Supplies controlled current to the motor windings
- Typically implemented with H-bridge MOSFET drivers and current regulation (chopper control)

In some systems, the indexer and power stage are integrated; in others, they operate as separate modules

Paulo Abreu ®

Stepper Motor Drivers
Core Power Electronics

Motor performance depends heavily on the driver, which has evolved from simple voltage control to modern vector-based strategies

- **The H-Bridge Power Stage**
  - A 2-phase stepper driver uses two H-Bridges, each built from four MOSFET switches
  - These switches allow reversing coil polarity, enabling electromagnetic control
- **Bipolar Driving**
  - By sequencing the MOSFETs, the driver can push current forward, reverse it, or disable it
  - This method delivers maximum torque density for 4-wire and 8-wire stepper motors
- **Electronic Commutation**
  - Unlike brushed DC motors with mechanical commutation, stepper motors rely on fully electronic switching
  - The driver must anticipate each step and commutate the H-Bridges accordingly to maintain smooth motion and torque

Paulo Abreu ®

47

Driver Architectures
L/R Drives vs. Chopper Drivers

L/R Drive (Constant Voltage) - the Old Legacy

These drivers apply a constant voltage to the windings. They rely on the resistance (R) of the coil to limit the current (I = V/R)

- **Limitation**: due to high inductance (L), the current rises very slowly. At high speeds, the current never reaches its peak before the next step is required, resulting in very poor high-speed torque

Chopper Drive (PWM/Constant Current) - the **Industrial Standard**

Modern drivers use Pulse Width Modulation (PWM) and a much higher supply voltage (e.g., using an 80V supply for a motor rated at 3V)

- **Operation**: the driver "blasts" the coil with high voltage to force the current to rise almost instantly. Once the target current is reached, the driver "chops" (switches) the voltage on and off rapidly to maintain that current
- **Benefit:** this overcomes the inductive "choke" effect, significantly extending the torque-speed curve

Paulo Abreu ®

48

Driver Architectures
Microstepping Control

U.PORTO FEUP FACULDADE DE ENGENHARIA UNIVERSIDADE DO PORTO

Microstepping is an electronic strategy where the driver modulates the current in the two phases to create a rotating magnetic vector that can stop between physical teeth.

- **Sine/Cosine Approximation**: instead of square waves, the driver sends stepped sine and cosine waves to the phases
- **Mechanical Damping:** by making the "steps" smaller, the driver prevents the rotor from overshooting and oscillating, which is the primary cause of audible noise and mechanical vibration in stepper systems

49

Paulo Abreu ®

Drivers and Control Strategies

U.PORTO FEUP FACULDADE DE ENGENHARIA UNIVERSIDADE DO PORTO

2. Control Strategies for Stepper Motors

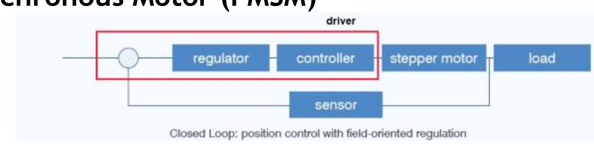
There are two main categories of control strategies

2.1 Open-Loop Pulse Control (Traditional Stepper Mode)

This is the classical method used in CNC machines, 3D printers, and low-cost positioning systems

2.2 Closed-Loop Vector Control (Servo-Like Control)

In this mode, the stepper motor is controlled similarly to a high-pole-count **Permanent Magnet Synchronous Motor (PMSM)**



50

Paulo Abreu ®

Open-Loop Pulse Control (Traditional Stepper Mode)

2.1 Open-Loop Pulse Control (Traditional Stepper Mode)

- Principle of Operation
  - The controller sends timed pulse commands; each pulse corresponds to a discrete step
  - Rotor position is assumed to follow the commanded magnetic field (synchronous stepping)
  - No position feedback is used
- Control Law
  - The position is computed as a discrete integration of input pulses: $\theta = \sum N \cdot \alpha$
  - To ensure synchronism, the available motor torque must exceed the required torque

$$T_m > Tloa_d + J\left(\frac{d\omega}{dt}\right) \; where\ J\ is\ the\ total\ inertia\ (motor\ +\ load).$$

- Limitations
  - Possible loss of steps under excessive acceleration, load, or resonance
  - Requires over-dimensioning
  - Resonance may occur at certain speeds

51

Paulo Abreu ®

Closed-Loop Vector Control (Servo-Like Control)

2.2 Closed-Loop Vector Control (Servo-Like Control)

Key Features

- Uses Field-Oriented Control (FOC)
- Controls torque and flux independently through the d-q reference frame
- Eliminates step loss and significantly reduces mechanical resonance
- Allows true control of torque, speed, and position

Feedback Options

1. **True Closed Loop** (FOC with Encoder/Resolver)
   - Rotor position measured via encoder or resolver
   - Enables high accuracy, high dynamic performance, and the elimination of missed steps
2. **Sensorless Vector Control** (FOC with Virtual Encoder)
   - Rotor position estimated from measured stator voltages and currents using the motor model
   - Lower performance at low speeds due to poor signal observability

52

Paulo Abreu ®

Field-Oriented Control (FOC) for Stepper Motors

FOC relies on transforming the three-phase (or two-phase for steppers) currents into two orthogonal components using **Clarke and Park transformations**:

- d-axis current i_d : produces flux
  - For stepper motors, usually regulated to zero for maximum efficiency and minimal heating
- q-axis current i_q : produces torque
  - Controlled to maintain a **90° electrical angle** between rotor and stator fields (Maximum Torque per Ampere – MTPA)

This decoupling enables smooth torque production, high efficiency, and servo-grade performance

Selection Criteria for Drivers

When integrating a driver into a mechanical system, the engineer must match the **driver** to the **motor's** electrical needs:

1. **Peak vs. RMS Current**: ensure the driver can handle the motor's rated current
2. **Voltage Overhead**: a higher voltage driver will always provide better high-speed performance
3. **Communication Interface**
   - **Pulse/Direction**: simple, real-time, universal.
   - **Bus-based (EtherCAT/CANopen)**: allows for complex multi-axis synchronization and diagnostic feedback (e.g., Beckhoff EL7047).

Advantages of Closed-Loop Stepper Systems

Closed-loop stepper motors combine the benefits of both steppers and servos

Performance Benefits

- No step loss—guaranteed positioning
- Reduced vibration and resonance
- Short settling times and stable low-speed operation
- High torque at low speeds (better than many servo motors)
- Lower cost than comparable servo systems
- High load tolerance and precise positioning without overshoot

Typical Applications

- Robotics, CNC, and precision automation
- Medical devices
- Semiconductor machinery
- Packaging machinery

(en.nanotech.com)

Stepper Motors
Thermal Management and Efficiency

Constant-Current Driving & Heat Generation

- **Traditional Stepper Operation**
  - Drivers supply a fixed current (e.g., 4.2 A) regardless of load
  - At zero speed, motor still draws full current → maximum heat with zero mechanical work
- **Why Steppers Run Hot**
  - Dominant loss: copper (I^2R) heating in windings
  - At low speed: efficiency ≈ 0% (all energy turns into heat)
  - At high speed: iron losses (eddy currents + hysteresis) increase

Paulo Abreu ®

U.PORTO FEUP FACULDADE DE ENGENHARIA UNIVERSIDADE DO PORTO

Stepper Motors
Thermal Management and Efficiency

Thermal Management & Motor Lifetime

- **Drivers with Idle Current Reduction (ICR)**
  - After inactivity (≈1 s), driver cuts current to ~50%
  - Heat drops by 75%, but holding torque reduces by 50%
- **Thermal Risks**
  - Bearing damage: heat dries grease → friction + wear
  - Demagnetization: excess temperature weakens rotor magnets
- **Motor Insulation Classes**
  - Class B: 130°C, Class F: 155°C allowable internal temps

Paulo Abreu ®

57

U.PORTO FEUP FACULDADE DE ENGENHARIA UNIVERSIDADE DO PORTO

Stepper Motors
Thermal Management and Efficiency

Advanced Control & Cooling Techniques

- **Driver with Closed-Loop / Field-Oriented Control (FOC)**
  - Current becomes load-dependent instead of constant
  - Near-zero current at idle → dramatically cooler, more efficient
  - Enables higher peak torque without overheating
- **Mechanical Heat Dissipation**
  - Aluminum mounts act as heat sinks; plastic traps heat
  - Industrial motors use finned housings for airflow
  - High-duty applications often add external fans

Paulo Abreu ®

58

Control Strategies for Stepper Motors Comparison Table

Feature	Open-Loop	Sensorless Vector Control (FOC with Virtual Encoder)	True Closed Loop (FOC with Encoder/Resolver)
Feedback	None	Mathematical Observer	Encoder/Resolver
Efficiency	Low (Constant Current)	High (Variable Current)	High (Variable Current)
Resonance	Significant	Damped (at higher speeds)	Actively Damped
Stall Risk	High	Low	Zero
Best For	"Low-cost fixed load"	"High-speed medium cost"	"High-precision variable load"

59

Examples of Industrial Solutions with stepper motors

- Stepper motors with integrated gearboxes
- Vector-controlled stepper solutions available in multiple Manufacturers include
  - Beckhoff – EtherCAT-compatible integrated stepper servo systems
  - Oriental Motor – AZ and AR series closed-loop steppers
  - Nanotec – C5-E, CL3-E and sensorless controller solutions

For further reference, see Nanotec's sensorless control documentation:
https://en.nanotec.com/fileadmin/files/Application_Notes/Sensorlose_Regelung/Sensorless_controll.pdf

Paulo Abreu ®

60

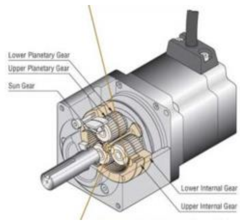
U.PORTO FEUP FACULDADE DE ENGENHARIA UNIVERSIDADE DO PORTO

Stepper motors with built-in gearboxes

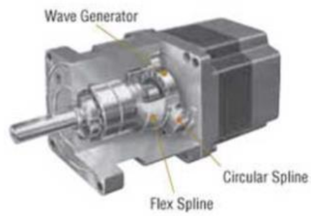
Some manufacturers of stepper motors offer versions with built-in gearboxes (gear head), in order to provide high torque drive solutions with compact size

- Types of gearboxes:

Tapered gears



Planetary gears



Harmonic gears

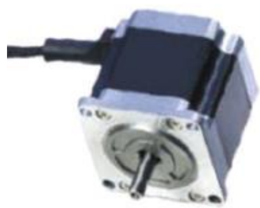
61 www.orientalmotor.com

U.PORTO FEUP FACULDADE DE ENGENHARIA UNIVERSIDADE DO PORTO

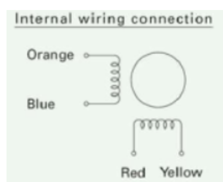
Stepper motors
Example solution from Beckhoff

Motor AS1030

- 2-phase Motor, 4 wires, hybrid (HB)
- Supply voltage 24 – 50 V DC
- Nominal current 1.5 A
- Nominal power 19.5 W
- Standstill torque 0.6 Nm
- Rotor inertia 0.21 Kg cm^2
- Step angle 1.8º, 200 steps per turn (full step)
- Flange size 42 mm (approx. NEMA 17)



www.beckhoff.com



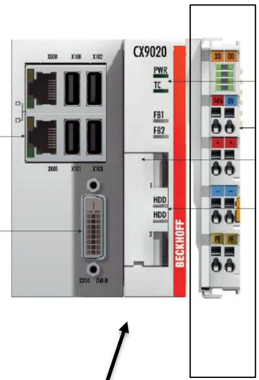
62

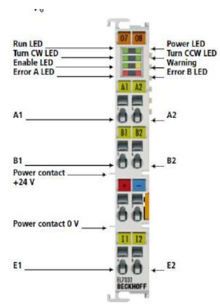
Stepper motors
Example solution from Beckhoff

Driver EL7031 to motor AS1030

- Driver to incorporate on embedded PC (ex. CX9020) that already supports the indexer and controller functions
- Nominal voltage 24 V DC, nominal current 1.5 A
- Two digital inputs
- Configuration with two parameters(one fixed!)
  - Scale factor: it is only possible to have 64 micro-steps per full step (64*200= 12800 micro-steps per turn)
  - Base frequency of 1000, 2000, 4000, 8000 steps/s (limit the maximum operating speed to 300, 600, 1200, 2400 rpm)

The EL7031 is a classic open-loop microstepping driver (chopper driver)





www.beckhoff.com

Embedded PC CX9020

Driver EL7013

63

Stepper motors
Example solution from Beckhoff

Operating motor AS1030, with driver EL7031 and controller CX9020E

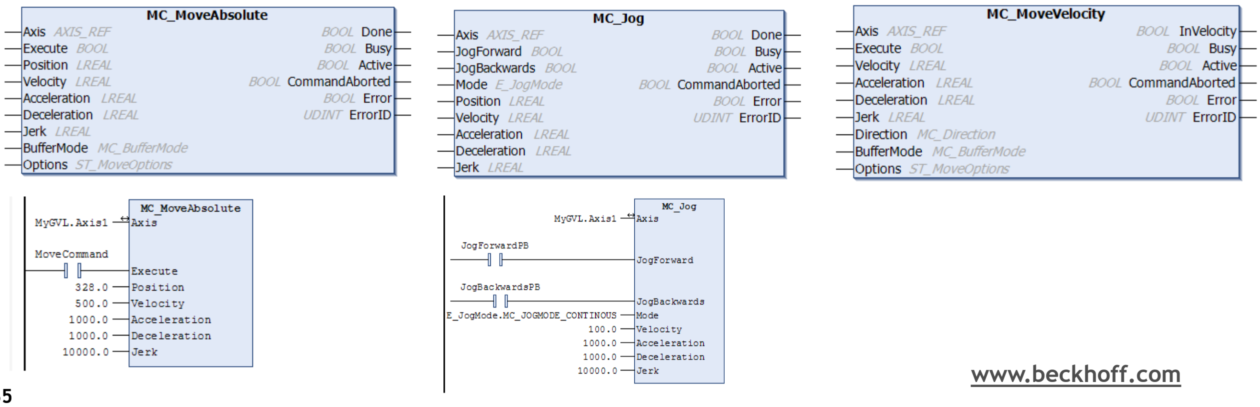
- Motion axis parameterization: **scale factor** and **base frequency**
- Use programming blocks (PLCOpen) with required motion (MC_Moveabsolute, MC_Jog, MC_MoveVelocity, …)
- Need to specify
  - Desired position or desired velocity
  - Definition of the motion acceleration and deceleration by
    - Direct specification of values
    - Specification of acceleration time and deceleration time
  - Definition of a value for jerk (variation of acceleration)

Paulo Abreu ®

64

Stepper motors
Example solution from Beckhoff

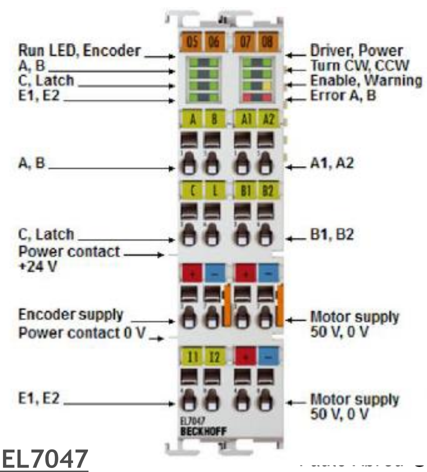
Operating motor AS1030, with driver EL7031 and controller CX9020E, with PLCopen block programming: examples



www.beckhoff.com

Stepper motors
Example solution from Beckhoff

- Beckhoff provides other drivers for stepper motors that allow implementing **vector control**
  - Driver EL 7047 with vector control (50V DC, 5A)
  - Use of encoder, closed-loop control, providing the reliability of a servo with the high-pole-count torque of a stepper
- Programming and functionality similar to those available for synchronous servomotors
  - The software layer (TwinCAT) sees the EL7047 as a standard "Axis," meaning the same code used for a 50kW Servo can run a 50W Stepper



Driver EL7047

Future Trends: Integrated Motors

The industry is moving toward "Integrated Steppers," where the motor, encoder, and driver are housed in a single unit

- **Reduced EMI**: high-power PWM switching is contained within the motor housing, reducing electromagnetic interference in the control cabinet
- **Simplified Wiring:** instead of 8 motor leads traveling through a long cable track, only a DC power pair and a communication cable (EtherCAT or CANopen) are required

Sources for info on stepper motors

Suppliers

- https://www.portescap.com/en/products/stepper-motors
- https://www.faulhaber.com/en/products/stepper-motors/
- https://en.nanotec.com/products/153-stepper-motors-from-manufacturer
- https://www.orientalmotor.com/stepper-motors/index.html
- https://www.igus.pt/e-motors/stepper-motor
- https://www.kollmorgen.com/en-us/products/motors/stepper/

Technical info

- https://en.nanotec.com/knowledge-base/category/stepper-motors
- https://www.orientalmotor.com/stepper-motors/technology/stepper-motor-basics.html