



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

Rotational and Linear Servomotors

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2026 Edition

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Rotational and Linear Servomotors

Paulo Abreu

March 2025

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Servomotors: Overview & Learning Outcomes

What you will learn

- Define a servomotor and a servo system and distinguish the motor from the closed-loop system in which it operates
- Describe PMSM construction (stator, rotor, magnets) and why PMSM is dominant for industrial servos
- Explain electronic commutation, FOC control, and the role of high-resolution transducer
- Outline industrial networking and functional safety
- Interpret torque-speed envelopes, duty classes, field-weakening, and braking methods
- Apply inertia matching, selection, and tuning basics to real applications

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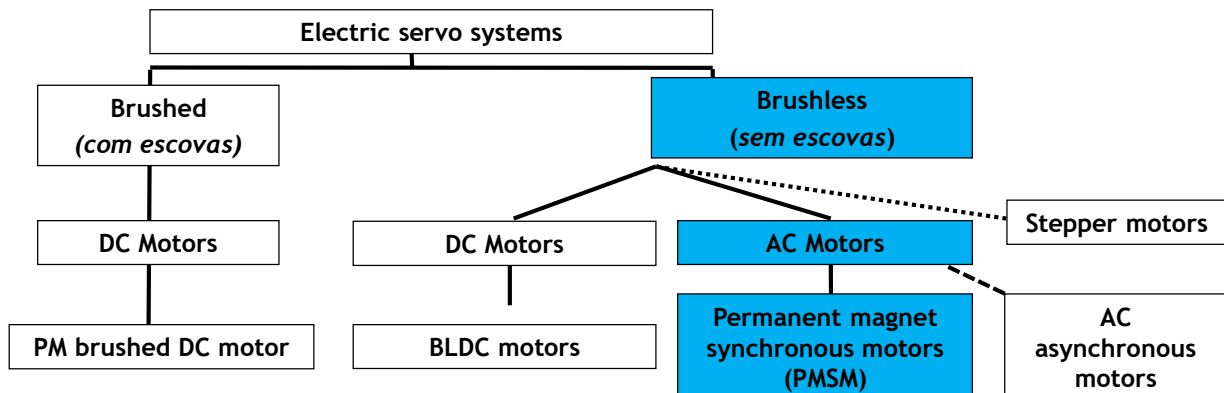
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Rotational and Linear Servomotors

Contents

- **Rotational Servomotors**
 - Definition & Context
 - PMSM Construction
 - Working Principle & FOC
 - Feedback Transducers
 - Servo Drives & Power Electronics
 - Industrial Standards & Safety
 - Performance Curves
 - Applications
 - Industrial examples
- **Linear servomotors**
 - Introduction to direct-drive linear motion
 - Core electromagnetic topologies
 - Mechanical & kinematic principles
 - Linear motor dynamic performance
 - Feedback and sensing architecture
 - Vector control in linear motors
 - Comparison with ball-screw systems
 - Industrial examples

Servomotors



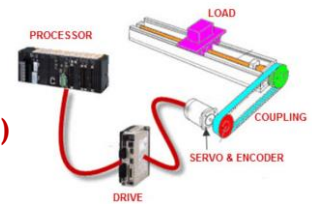
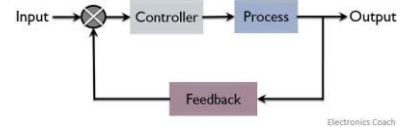
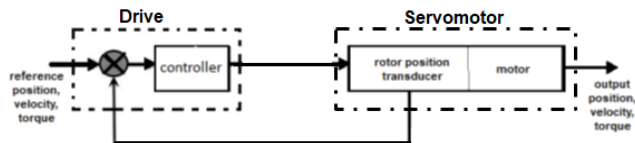
Servomotor Technology

- A servo system is a closed-loop motion system that controls position, speed, or torque using feedback transducer (encoder/resolver) and a servo drive

Servo system (drive + feedback + controller + motor)

- A servomotor is the actuator within that system—most commonly a Permanent-Magnet Synchronous Motor (PMSM) paired with a high-resolution transducer

Servomotor (hardware motor with rotor position transducer)



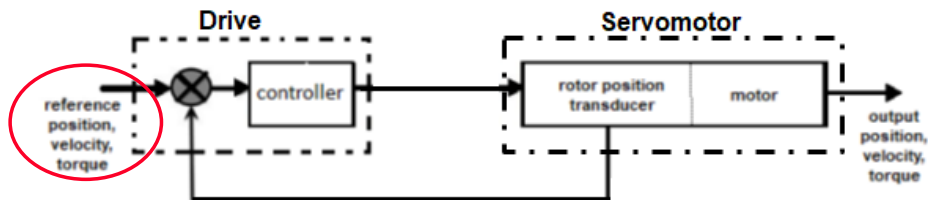
See video from [Yaskawa](https://www.youtube.com/watch?v=...)

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Servomotor Technology

Servomotor



Distinction: While various motors (DC brushed, BLDC, Stepper, Induction) can be used in closed-loop control systems for regulating position, velocity, and torque, the term "servomotor" typically refers to a **Permanent Magnet Synchronous Motor (PMSM)**, with a built-in high-resolution transducer (encoder or resolver)

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Servomotors (PMSM) versus DC Brushed, Steppers, Induction

- **DC brushed:** simple control; the brushes introduce friction, wear, electrical arcing, limited speed, and periodic maintenance requirements
- **Stepper:** open-loop positioning common; limited high-speed torque, and coarse movement resonance/cogging at speed; hybrid closed-loop steppers exist but have lower dynamic bandwidth due to detent torque and high inductance, and limited operation speed, when compared to PMSM
- **Induction:** typically operated in open-loop scalar (V/f) control, suitable for basic speed regulation. With vector control (closed-loop), induction machines can achieve improved performance, but they still exhibit lower torque density, lower bandwidth, and slower dynamic response than PMSM
- **PMSM:** servomotor brushless, high bandwidth, smooth torque, excellent low-speed control, high efficiency; ideal for dynamic multi-axis automation

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PMSM Construction and Working Principle

The PMSM is an AC synchronous motor where the "synchronous" part means the rotor rotates at the exact same speed as the magnetic field produced by the stator

The Stator: similar to a standard induction motor, the stator consists of a laminated iron core with three-phase windings (U, V, W) distributed 120° apart. When excited by the drive's inverter, windings produce a **Rotating Magnetic Field (RMF)**

The rotor's permanent magnets lock onto this RMF, causing the rotor to spin at the synchronous speed (zero slip)

In PMSM, the **heat** is generated in the **stator** (outer shell). This is much easier to cool (via fins or liquid jackets) than a DC motor, where heat is generated in the internal rotor

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PMSM Construction and Working Principle

The Rotor

The rotor features **High-Energy Permanent Magnets** (typically Neodymium-Iron-Boron)

- **Rotor Two principal designs**
 - SPM (surface-mounted): low inertia; very smooth; ideal for fast dynamics.
 - IPM (interior/buried): mechanically robust; exhibits saliency and provides reluctance torque in addition to PM torque → higher peak torque, better field-weakening
- **High Torque-to-Inertia Ratio**: because the rotor is relatively light (permanent magnets vs. heavy copper windings), it can accelerate and decelerate very rapidly

Other Mechanical components

- Shaft/bearings, optional fail-safe brake (spring-applied, 24 VDC released)

Synchronous Operation & Back-EMF

In a PMSM, the rotor locks to the stator's rotating field → synchronous speed (electrical slip ≈ 0)

Back-EMF (E): the magnets and windings are designed so that the voltage generated when the motor spins (Back-EMF), that is proportional to speed, is a perfect sine wave. This allows for smooth motion without the "torque ripple" found in some low-cost BLDC motors

- $$E = K_e \cdot \omega$$

In SI units, **torque (K_t)** and **back-EMF (K_e)** constants are equal numerically:

- $$K_t [N \cdot m/A] = K_e [V \cdot s/rad]$$

Servomotor (PMSM) Construction and Architecture

A PMSM cannot operate directly from the electrical grid. It requires a **servo drive** and a **feedback transducer**. The drive aligns the stator current vector optimally relative to the rotor flux.

Integrated Feedback Transducer

- Every PMSM includes high-resolution **encoders** or **resolvers** to provide absolute or incremental position, enabling the drive to optimally align the stator current vector at every instant

Electronic Commutation

- No brushes: the servo drive switches currents electronically
- An encoder/resolver reports rotor position so the drive always aligns the stator magnetic field so it aligns in optimal opposition to the rotor magnets (space commutation)

Servo Drive with Vector Control (Field-Oriented Control)

- Using the feedback transducer, the servo drive uses Field-oriented Control (FOC). It mathematically transforms the three-phase currents into dq components (I_d and I_q) to independently and efficiently regulate flux and torque

Servomotor (PMSM) Working Principle

■ Servo Drive uses Field Oriented Control (FOC)

- Controls the motor by regulating d- and q-axis currents (I_d, I_q), enabling accurate torque, speed, and position control
- The servo drive calculates the required electrical frequency based on rotor position feedback, speed commands, and the Field-Oriented Control (FOC) algorithm (frequency and voltage are not set directly!)

■ Back-EMF and Smooth Motion

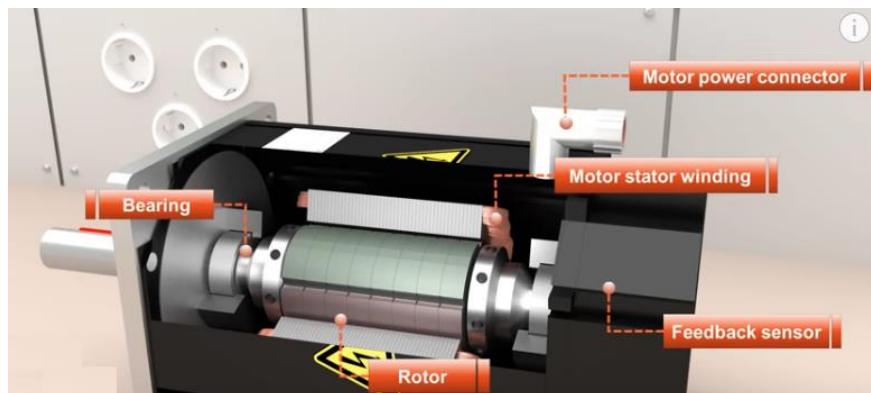
- Spinning rotor magnets induce a Back-EMF in the stator coils
- The drive outputs matching voltages to reduce vibration and torque ripple → very smooth, precise motion

Servomotor (PMSM) Construction and Architecture

Component	Material/Technology	Function
Stator	Laminated Silicon Steel / Copper	Creates the rotating magnetic field
Rotor	Neodymium (NdFeB) Magnets	Provides a constant magnetic field without electrical loss
Feedback	Encoder / Resolver	Reports rotor position to the drive for commutation
Cooling	Convection / Liquid	Dissipates heat from stator windings

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Servomotor (PMSM) Construction/ Working Principle



<https://youtu.be/hg3TIFxWCo> and <https://youtu.be/Gzo9m0tMDQA>

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Servomotor (PMSM) Applications

Servomotors are used in applications that require

- Superior precision in **position** control or **speed** or **torque** control
- Speed control over an extended range of torque
- Static torque at zero speed
- Overload capability
- High dynamic performance

Applications Fields

- Robotics and Automated Guided Vehicles (AGVs)
- CNC Machine Tools and Metalworking
- Food, Beverage, and Packaging Industry
- **Aerospace and Electric Traction**
- Medical and Laboratory Equipment

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Servomotor (PMSM) Example from Beckhoff

Main parts

- Servomotor ([AM8021](#))
- Servo drive [AX5103](#)
- High resolution identification of rotor position using an absolute encoder

Note the use of “One Cable Technology” - OCT (the same cable for power and signal)



The drive is fundamental!

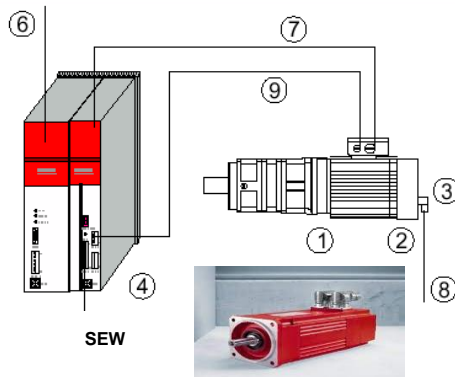
- The motor does not work without a drive
- The drive must support the encoder interface
- Drive output frequency and output current, together with the motor, dictate maximum speed and torque

Servomotor ([AM8021](#))
and servo drive [AX5103](#)
from [Beckhoff](#)

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Servomotor (PMSM) Example from SEW



SEW CMP series servomotors

1. Motor (with /without gearbox)
2. Feedback element
3. Brake (optional)
4. Servo drive

6. Power cable
7. Motor power cable
8. Brake power cable
9. Feedback transducer cable

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Feedback Systems Encoders: Types & Signals

Incremental Encoder (Digital Output)

- Differential A_{\pm} , B_{\pm} in quadrature + Z_{\pm} (index)
- Position from pulse count
- X4 decoding increases counts (e.g., 1000 LPR -lines per revolution \rightarrow 4000 PPR - pulses per revolution)
- Optical sensing

SinCos Encoder (Analogue Output)

- Analog sin/cos waveforms per mechanical period
- The drive interpolates to 18-24+ bit equivalent resolution
- may use optical or magnetic sensing

Absolute encoders

- Single-turn (absolute angle within one revolution) and multi-turn (also counts revolutions)
- Battery, mechanical mechanism, or energy-harvesting for memory
- Interfaces: BiSS-C, SSI, SPI, EnDat (HEIDENHAIN), Hiperface (SICK/Stegmann)

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Feedback Systems Resolvers: Robust Absolute Sensing

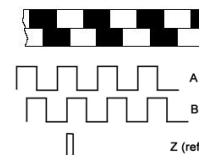
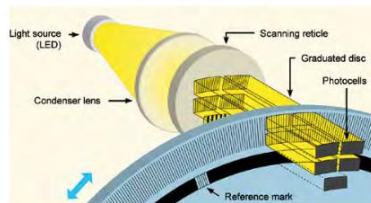
Resolvers (Analogue Output)

- Electromagnetic rotary transducer: an excited rotor couples to two stator coils displaced 90°
- Idealized outputs:
 - $V_{sin} = k \cdot V_{ref} \cdot \sin(\theta)$
 - $V_{cos} = k \cdot V_{ref} \cdot \cos(\theta)$
- A Resolver-to-Digital Converter (RDC) computes angle θ and speed
- Excellent for harsh environments (vibration/temperature/radiation)
- Absolute within a single turn; multi-turn requires external counting

Feedback Systems and Position Measurement Incremental Encoder

Incremental Encoder (Digital output)

- Provide position and direction information. The position is given by counting the number of pulses
- Optical operating principle
 - The light beam passes through a linear scale or graduated disc, being detected by photodetectors
 - The encoder provides three digital signals, **A**, **B**, from the two tracks, and **Z** (Index Pulse or Reference Mark), a single pulse per revolution, used to establish a "Home" position
 - The two signals A and B are out of phase by 90° in quadrature (allowing the discrimination of the direction of rotation). If A leads B, it's CW; if B leads A, it's CCW

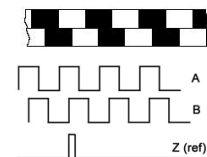
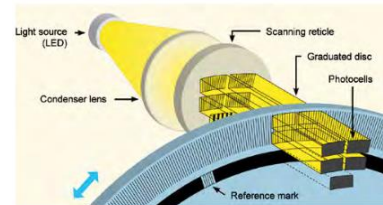


See [video](#)

Feedback Systems and Position Measurement Incremental Encoder

■ Resolution Enhancement (X4 Encoding)

- The physical resolution is determined by the number of pulses per revolution (PPR)
- However, the drive can use “X4 Encoding” by counting every rising and falling edge of both channels. This quadruples the measurement resolution (e.g., a 1000 LPR graduated disc provides 4000 distinct positions per turn)



See [video](#)

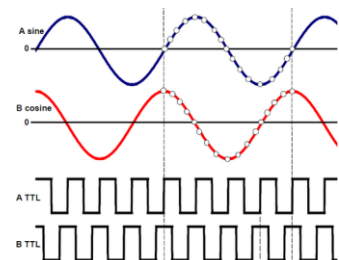
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Feedback Systems and Position Measurement SinCos Encoder

SinCos encoder (analogue output)

- Provide position and direction information .The position is obtained through the generation and reading of two analog signals, allowing high resolution
- Working principle
 - Use of inductive sensors
 - Availability of two low-voltage analog signals, 90° out of phase, (Sin and Cos)
 - After interpolation, electronics provide digital outputs, similar to the encoder (typical settings of 8192 increments per revolution (13 bits) or even 262144 (18 bits) or 16777216 (24 bits)



See
[video](#)

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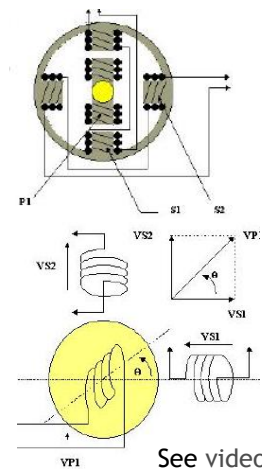
Feedback Systems and Position Measurement Resolver

The Resolver: Electromagnetic Rotary Transducer

The Resolver is an analog electromagnetic transducer used to measure the absolute angular position of a shaft within a single revolution (360°)

Working Principle

- Resolvers have an excited rotor, where its coil is powered with a high-frequency alternating reference voltage (V_{ref})
- Induction: this rotating magnetic field induces voltages in two stationary stator coils (Sine and Cosine) that are physically oriented 90° apart
- Signal Output: the amplitude of the induced voltages varies based on the sine and cosine of the shaft angle (γ)
- Processing: a Resolver-to-Digital Converter (RDC) processes these analog signals to provide high-resolution digital position and velocity (rotational speed) data to the servo drive



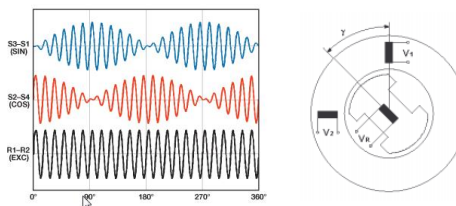
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Feedback Systems and Position Measurement Resolver

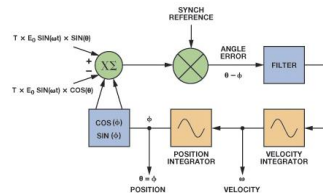
Resolver

Angular position analog transducer

- Rotor powered by alternating voltage $V_{ref} = V_s^* \sin(\omega t)$
 - Measurement of the induced voltage in V_{sin} and V_{cos}
 - $V_{sin} = V_s \cdot \sin(\omega t) \cdot \sin(\gamma)$
 - $V_{cos} = V_s \cdot \sin(\omega t) \cdot \cos(\gamma)$
- where γ is the angle of the rotor relative to the winding



- A “Resolver to Digital Converter- RDC” processes the signals from V_{sin} and V_{cos} to obtain the angular position and rotational speed of the shaft (e.g. AD2S1210, variable resolution, 10-Bit to 16-Bit R/D Converter with reference oscillator)



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Feedback Systems and Position Measurement Resolver

- **High Robustness:** resolvers have no electronics or glass disks inside the servomotor (Note the drive has to have RDC electronics!). This makes them the only choice for high-vibration, high-temperature, or radioactive environments where an optical encoder would fail

- **Performance Summary**
 - **Position Type:** Absolute (within one turn)
 - **Output:** Analog (Sin/Cos waves)
 - **Reliability:** Highest among all feedback transducers
 - **Primary Use:** Heavy-duty servomotors, aerospace actuators, and EV traction motors

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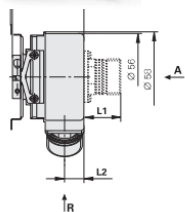
Comparison

	Digital Encoder	SinCos Encoder	Resolver
Precision	Medium	Very High	Low/Medium
Robustness	Low (Glass disk)	Low (Electronics)	Extreme
Cost	Low	High	Medium
Interface	Pulse/Dir	Analog/Digital	Analog

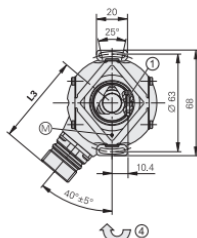
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Incremental encoder from Heidenhain

Encoder model ERN 420



ERN 400 Serie



www.heidenhain.com

Incremental	
ERN 420	
Interface	TTL
Line counts*	250 500
	1000 1024 1250 2000 2048 2500 3600 4096 5000
Reference mark	One
Cutoff frequency -3 dB	-
Output frequency	≤ 300 kHz
Edge separation α	≥ 0.39 μ s
System accuracy	1/20 of grating period
Electrical connection*	<ul style="list-style-type: none"> M23 flange socket, radial and axial (with blind hollow shaft) Cable 1 m, without connecting element
Supply voltage	DC 5 V ± 0.5 V
Current consumption without load	≤ 120 mA
Shaft*	Blind hollow shaft or hollow through shaft; D = 8 mm or D = 12 mm
Mech. permissible speed n^{II}	6000 rpm/5 12 000 rpm ^{III}
Starting torque (typical) at 20 °C	Blind hollow shaft: 0.01 Nm Hollow through shaft: 0.025 Nm (for IP66: 0.075 Nm)
Moment of inertia of rotor	≤ 4.3 · 10 ⁻⁶ kgm ²
Permissible axial motion of measured shaft	± 1 mm
Vibration 55 Hz to 2000 Hz	≤ 300 m/s ² ; flange socket version: 150 m/s ² (EN 60068-2-6); higher values up to 2000 m/s ² (EN 60068-2-27)
Shock 6 ms	
Max. operating temperature*	100 °C

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General purpose Encoder from JVL

- Multiple options: model PA0260 General purpose encoder PCB that can be mounted on all kind of stepper or servomotor. Incremental or absolute multi-turn encoder with incremental ABZ signals, SinCos signals or SSI or BiSS-C interface. Resolution from 128 to 65536 cnt/rev
 - A+,A-,B+-,B-,Z+,Z- signal 5V or 24V RS422
 - Factory programmed Resolution of 128, 256, 512, 1024, 2048, 4096, 8192, 16384 cnt/rev
 - Up to 16-bit Interpolated resolution 32768, 65536 cnt/rev
 - Absolute resolution of 0.02° (14 bit / 360° at up to 10000 rpm)
 - Integrated RS422 transceiver up to 10 Mbit/s
 - 5V to 30V supply and signals
 - Optional SIN+/-/COS+/- signals. Diff. current-limited sin/cos outputs (1 Vpp to 100 Ω)
 - Optional absolute multi-turn encoder with the internal or external battery up to 15 years lifetime; resolution 4096 turns (12 bit); Absolute multi-turn signals out on BiSS, SSI or SPI



BiSS Standard Protocol (BP1, BP3)
SSI - Serial Synchronous Interface
SPI - Serial Peripheral Interface

<https://www.jvl.dk/1168/pa0260-encoder>

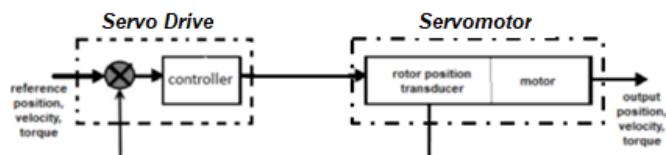
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Servo Drives and Power Electronics Servo Drive

The Servo Drive

Servomotors require a power source compatible with their design. The **servo drive** fulfils this function

The servo drive provides power to the servomotor so that it is possible to control position, velocity and torque in response to inputs from the motion controller, feedback encoder/resolver and the servomotor itself



SINAMICS V90 servo converter and the SIMOTICS S-1FL6 servomotor, from [Siemens](#)
The system features eight converter frame sizes and seven motor shaft heights to cover a power range of 0.05 to 7.0 kW for operation in single-phase and three-phase networks
[video](#)

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Servo Drives and Power Electronics Power Electronics Architecture

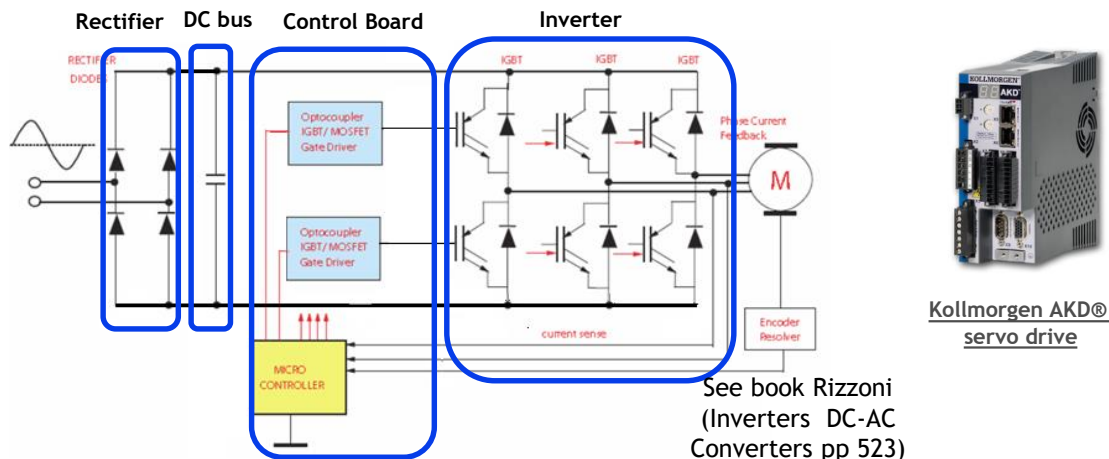
The internal power stage of a servo drive is responsible for converting the **AC grid power into a controlled variable-voltage output**

- **Conversion / Rectifier Stage:** converts the incoming AC mains voltage (e.g., 400V) into a raw DC voltage
- **DC Bus (The Capacitor Bank):** acts as an energy reservoir. It smooths the DC voltage and stores energy returned by the motor during braking
- **Inverter:** the most critical part. It uses high-speed electronic switches - IGBTs (Insulated Gate Bipolar Transistors) or fast MOSFETs - to convert the DC back into a **3-phase PWM** voltages to enforce commanded currents
- **Control Board** performs FOC, loop control, protection, and communication

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Servo Drives and Power Electronics Power Electronics Architecture



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Servo Drives and Power Electronics PWM & Current Smoothing

Pulse Width Modulation (PWM)

Since the drive cannot vary the DC bus voltage directly, it uses PWM to create an analog sine wave

Principle:

- High-frequency switching (typ. 4-16 kHz) using the IGBTs modulates phase voltages. By varying the "duty cycle" (the ratio of ON time to OFF time), the drive controls the effective voltage.
- Motor inductance smooths phase currents → near-sinusoidal currents for low torque ripple
- EMI (electromagnetic Interference), dv/dt (rate of voltage change over time) stresses motor insulation, and cable length considerations require proper shielding and filters

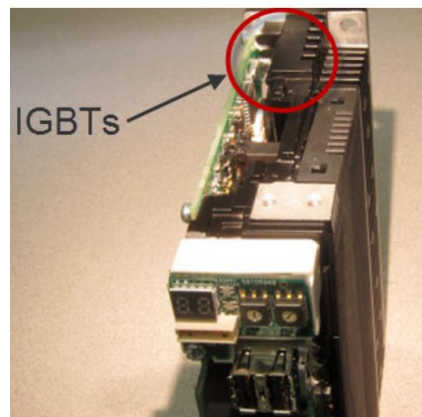
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Servo Drive

A servo drive does not command voltage, frequency, and phase individually. Instead, in Field-Oriented Control (FOC) drives:

- The IGBTs (or MOSFETs) are switched via PWM patterns generated by the control processor
- These switching patterns synthesize the required 3-phase voltages and currents
- The drive controls current vectors (I_d, I_q); from those, the appropriate voltage, frequency, polarity, and phase emerge automatically



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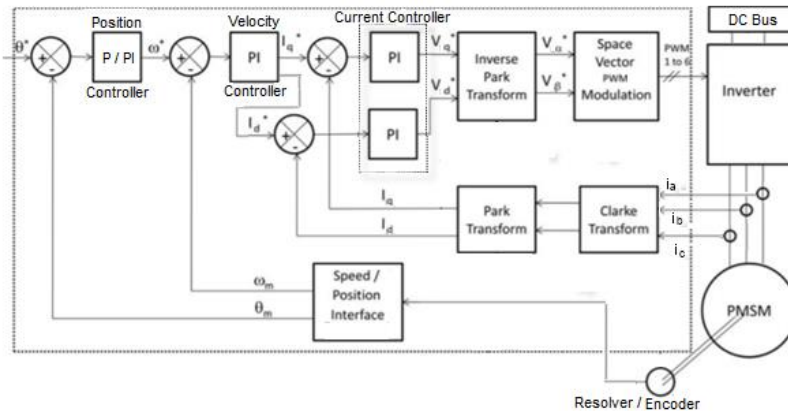
FIELD-ORIENTED CONTROL (FOC) AND DQ DYNAMICS

- **dq Reference Frame Transformation**
 - Clarke and Park transformations convert three-phase stator currents to a rotating dq frame aligned with the rotor magnetic field
- **Torque and Flux Control**
 - d-axis current (I_d) controls magnetic flux, while q-axis current (I_q) generates torque for PMSMs in Field-Oriented Control
- **Nested Control Loops**
 - FOC uses fast inner current loop, slower speed loop, and outer position loop for precise servo motion control
- **High-Speed Operation and Limitations**
 - At high speeds, back-EMF limits voltage vectors, introducing corner speed and constant-power operation concepts

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PMSM Control Architecture Based on Field-Oriented Control (FOC)



- θ_m and θ^* are the measured and reference rotor angle, respectively
 - ω_m and ω^* are the measured and reference angular velocities, respectively
 - i and v are stator currents and voltages and subscripts d and q represent the d -axis and q -axis, and subscripts $a, b,$ and $c,$ represent the three stator windings
 - subscripts $a, b,$ and c represent the three stator windings
 - Clarke, Park, and inverse Park transforms to convert between stationary (α, β) and rotating synchronous frames (d, q)
- Paulo Abreu ©

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Control Fundamentals (FOC & Loops) Control-Loop Architecture - Big Picture

Multi-Loop Cascade

Modern servo drives use a three-loop cascaded structure to achieve high bandwidth, disturbance rejection, and precise trajectory tracking:

- 1. Position Loop (Outer)**
 - Computes position error
 - P or PI controller, often preceded by a trajectory/profile generator
 - Outputs a speed reference
- 2. Speed Loop (Middle)**
 - PI controller regulates angular velocity ω
 - Outputs a torque-producing current reference i_q
- 3. Current (Torque) Loop (Inner)**
 - Fastest loop; high-bandwidth PI controllers for i_d and i_q
 - Ensures accurate current tracking despite disturbances (e.g., load steps, inverter nonlinearities)

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Field-Oriented Control (FOC) & dq Transformation

dq Reference Frame

Three-phase stator currents are mapped into a rotating dq-frame aligned with the rotor flux:

- I_d - flux-producing component
- I_q - torque-producing component

This transformation decouples torque and flux, enabling independent regulation through PI controllers

Optimal Use of I_d for PMSM Types

- **SPM (Surface-Permanent-Magnet) motors**
 - Nearly non-salient: $L_d \approx L_q$
 - MTPA occurs around $I_d \approx 0 \rightarrow$ maximum torque per amp achieved by keeping flux constant
- **IPM (Interior-Permanent-Magnet) motors**
 - Salient: $L_d \neq L_q$
 - MTPA requires negative I_d to exploit the reluctance torque component.
 - Negative I_d partly demagnetizes the air-gap flux, reducing required I_q

Field-Oriented Control (FOC) & dq Transformation

Field-Weakening (High-Speed Operation)

At high speeds, back-EMF approaches inverter voltage limits.

To remain within the voltage limit, the controller:

- Injects more negative I_d
- Reduces net flux linkage
- Allows operation above base speed (constant-power region)

PMSM Torque

For a PMSM with p pole pairs, the electromagnetic torque is:

$$T = \frac{3}{2}p (\psi_m I_q + (L_d - L_q) I_d I_q)$$

Where: ψ_m - PM flux linkage
 L_d, L_q inductances

Interpretation for SPM Machines

- $L_d \approx L_q \rightarrow$ reluctance term vanishes. Torque simplifies to: $T \approx \frac{3}{2}p (\psi_m I_q)$
- Torque is almost entirely from PM torque; controlled by I_q

Interpretation for IPM Machines

- $L_d \neq L_q \rightarrow$ reluctance torque exists
- Extra term $(L_d - L_q) I_d I_q$ significantly boosts torque capability
- Enables: higher peak torque, improved efficiency under MTPA and better field-weakening characteristics

Voltage Limit & Corner Speed

Inverter Voltage Constraint

Approximate steady-state voltage requirement:

$$V_{max}^2 \approx \omega_e^2 \left((L_d I_d + \psi_m)^2 + \omega_e^2 (L_q I_q)^2 \right) + (\text{resistive terms})$$

Where: ω_e = electrical angular speed
 V_{max} = maximum inverter phase voltage

Corner Speed

- Occurs when required voltage = available inverter voltage
- Beyond this point:
 - Torque must drop unless field-weakening is applied; Operation transitions from constant-torque to constant-power

Field-Weakening Mechanism

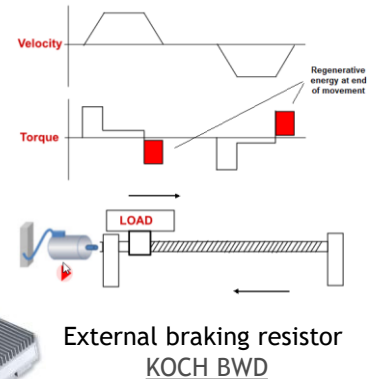
- Controller injects negative I_d to reduce effective flux
- Shrinks $L_d I_d + \psi_m$ term
- Ensures voltage stays within the inverter's capability
- Allows continued acceleration above base speed

Braking & Energy Management

Energy Management and Braking

- When a servomotor decelerates a load, the machine acts as a **generator**, returning energy to the **DC bus** of the drive
- If the bus voltage exceeds a predefined threshold, a brake chopper activates:
 - Excess energy is diverted to a braking resistor, where it is safely dissipated as heat (**dynamic braking**).
- For high-duty industrial systems, a **regenerative unit** can be used:
 - Returns energy back to the AC mains, improving system-level efficiency

Note: The braking capability depends on the drive, bus capacity, and resistor sizing, not just the motor



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Industrial Standards in Drives

Communication Standards in Servo Drives: Fieldbus and Real-Time Ethernet

- **EtherCAT (Ethernet for Control Automation Technology):** the standard used by Beckhoff. It is highly deterministic, allowing cycle times below 100µs. This is critical for synchronized multi-axis motion
- **CANopen (DS402 Profile):** a standardized device profile for motion control. It defines how objects like "Target Position" and "Actual Velocity" are mapped in the drive's memory, ensuring that a Nanotec drive and a Beckhoff drive can be swapped with minimal code changes
- **PLCopen Motion Control:** a set of standardized Function Blocks (e.g., *MC_MoveAbsolute*, *MC_Power*) that ensure the programming logic remains independent of the hardware manufacturer

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Hardware Standards: Protection and Feedback

- **Ingress Protection (IP Ratings)**

Industrial servomotors must meet standards like IP65 (dust-tight and protected against water jets) or IP69K (for food-grade wash-down environments)

- **UL/CE Marking**

Certification ensuring the electrical insulation and electromagnetic compatibility (EMC) meet North American and European safety laws

- **One-Cable Technology (OCT)**

A modern standard where power and feedback (encoder) are sent through a single shielded cable. OCT reduces cable count and cross-coupled EMI, but motor phase EMI remains

Core Safety Functions (IEC 61508 / ISO 13849)

- **STO (Safe Torque Off)**

- Hardware-level disabling of power-stage gating, so that motor cannot generate torque
- Maintains fast restart since the drive remains powered

- **SS1 / SS2 (Safe Stop 1 / Safe Stop 2)**

- SS1 Monitoring of controlled deceleration
- SS2 Transition to a torque-controlled hold state

- **SOS (Safe Operating Stop)**

- Motor is energized but monitored to ensure it holds a defined position window.

- **SLS / SLP / SDI / SBC**

- SLS Safely-Limited Speed; SLP Safely-Limited Position; SDI Safe Direction; SBC Safe Brake Control (monitored actuation of mechanical brake)

Functional Safety in Drives

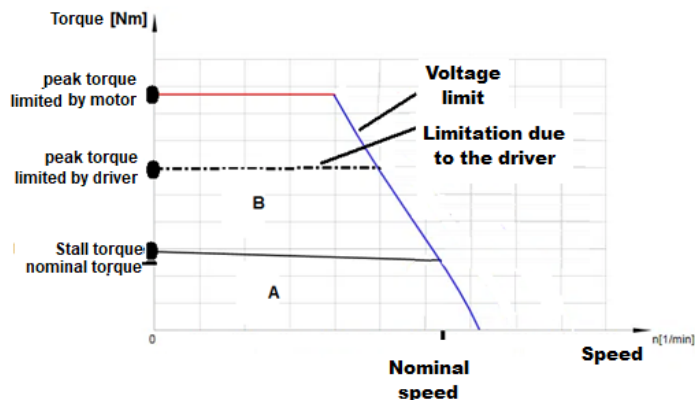
Safety over Fieldbus (FSoE)

The current "Gold Standard" is Fail Safe over EtherCAT (FSoE)

- Instead of hard-wiring safety signals to every drive, the safety data is sent as a "black channel" over the standard EtherCAT cable
- If the communication is interrupted or the safety PLC detects a fault, every drive on the network enters its defined "Safe State" (usually STO - Safe Torque Off)

Performance Characteristics and Torque-Speed Curves

The performance of a PMSM servomotor is not defined by a single point, but by an operating area. This area is bounded by the thermal limits of the motor and the electrical limits of the drive



Notice the impact of voltage limitation for the motor - servo drive combination on the Torque-Speed curve

A - permanent duty zone (S1)
 B - intermittent duty zone (S3)

www.fagorautomation.com

Performance Characteristics and Torque-Speed Curves

The Two Primary Operating Zones

- **Zone A: Continuous Duty (S1):** the area where the motor can operate indefinitely without overheating. The torque in this region is limited by the motor's ability to dissipate heat
- **Zone B: Intermittent Duty (S3):** the area where the motor can operate for short bursts (acceleration/deceleration). The torque here is limited by the maximum current the drive can supply or the magnetic saturation of the motor

Torque Limitation (Current Limit)

- At low speeds, torque is constant ($T = K_t \cdot I$)
- The horizontal line at the top of the graph represents the Stall Torque or Peak Torque, limited by the drive's maximum current output

Performance Characteristics and Torque-Speed Curves

Influence of the Servo Drive

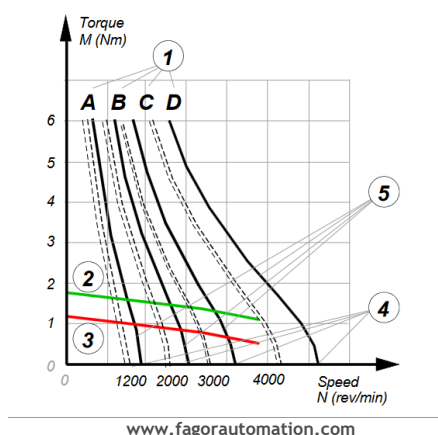
A motor's performance is inseparable from its drive

- **The impact of the Mains Voltage**
 - A motor connected to a 400V drive will have a much higher "Corner Speed" than the same motor connected to a 220V drive
 - This allows for higher mechanical power ($P = T \cdot \omega$) even if the torque remains the same
- **Drive Current Rating**
 - If the drive is undersized, the Peak Torque (Zone B) will be "chopped" or limited, even if the motor is capable of more

Performance Characteristics and Torque-Speed Curves

- **The Voltage Limit (Corner Speed and Field Weakening)**
 - As speed increases, the motor generates Back-EMF. When the Back-EMF plus the internal voltage drops equals the supply voltage from the drive, the motor reaches its **Corner Speed**
 - Beyond this point, the drive cannot "push" more current into the motor, and torque drops off rapidly, and transition to field weakening mode. This is known as the **Voltage Limit Curve**
- **Duty Cycles**
 - S1 (Continuous): the RMS torque of the entire cycle must fall within this zone
 - S3 (Intermittent): calculated based on a percentage (e.g., S3-25% means 2.5 minutes of load in a 10-minute cycle)
- **Thermal Management**
 - Some servomotors include internal thermistors (KTY or PT1000) that allow the drive to "fold back" current or trip a fault if the motor stays in Zone B for too long

Torque-speed curve for FAGOR servomotor



VOLTAGE LIMITS CHARACTERISTICS

—————	MAINS VOLTAGE: 400 Vrms, MOTOR VOLTAGE: 400-4.5%: 382 Vrms
-----	MAINS VOLTAGE: 220 Vrms, MOTOR VOLTAGE: 220-4.5%: 210 Vrms
-----	MAINS VOLTAGE: 400-15%: 340 Vrms, MOTOR VOLTAGE: 400-15%: 325 Vrms
-----	MAINS VOLTAGE: 220-15%: 187 Vrms, MOTOR VOLTAGE: 220-15%: 179 Vrms
-----	MAINS VOLTAGE: 400-10%: 360 Vrms, MOTOR VOLTAGE: 400-10%: 344 Vrms

1. Curves for torque limitation by voltage depending on type of stator winding.
2. Curve for thermal torque limitation in continuous duty S1 (100 K) with fan where $\Delta T=100$ K at the winding.
3. Curve for thermal torque limitation in continuous duty S1 (100 K) without fan where $\Delta T=100$ K at the winding.
4. Maximum turning speed limitation (in voltage) Nmax.
5. Voltage saturation curves.

Characteristic plate for a FAGOR servomotor

		8 3 4		2		1				
		FAGOR		AC BRUSHLESS SERVOMOTOR Fagor Automation S. Coop. San Andrés Auzoa 19, 20500 Arrasate-Mondragón Made in Spain		CE				
		Type FKM42.30A.E3.110-K03		Ver: 01		SN.: 128005003031234				
6	Mo	11 Nm	Io	7.2 A	Nominal speed: 3000 rpm				11	
7	Mmax	44 Nm	Imax	23 A	B.E.M.F.: 275		Iso.Cl: F		10	
		BRAKE 24VDC		IP 64		W: 11.4 kg		Bal.Cl: N		12
		15		5		9 13 14				

1	QR code / Serial Nr	9	Degree of protection
2	Version	10	Insulation class
3	Postal address	11	Rated speed
4	Current without load	12	Level of vibration
5	Maximum current	13	Mass
6	Stall torque	14	Back Electro Motor Force
7	Maximum torque	15	Holding brake (unlocking voltage/power absorbed)
8	Motor model reference		

[datasheet](#)

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Case Study: Beckhoff AX5103 Servo Drive

Servo Drive AX5103

- Dedicated to a single servomotor
- Power supply: 1 phase 100-240 VAC or 3 phases 100-480 VAC
- Supply current: 1 phase 5.7 A or 3 phases 3.3 A
- Auxiliary voltage supply: 24 V DC, 3A
- Nominal output voltage: 3 phases, 0 up to VAC (supply voltage)
- Output current nominal/maximum 3A / 7.5 A
- Output frequency: 0 to 599 Hz
- Switching frequency (8 or 16 kHz)
- Connection to motor and position transducer with “one cable technology”
- Digital I/O and EtherCat



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Case Study: Beckhoff AM8021 Servomotor

Electrical data	AM80xx	
	21B	21D
Standstill torque M_s [Nm]	0.50	0.50
Standstill current I_{srm} [A]	0.85	1.60
Maximum mechanical speed N_{max} [min ⁻¹]	12000	
Maximum rated mains voltage U_N [V _{AC}]	480	
Peak current I_{omax} [A]	4.90	8.60
Peak torque M_{omax} [Nm]	2.68	2.67
Torque constant K_{trms} [Nm/A]	0.59	0.31
Power supply $U_N = 115$ V		
Nominal speed N_n [min ⁻¹]	1500	3500
Rated torque M_n [Nm]	0.50	0.50
Rated output P_n [kW]	0.08	0.18
Power supply $U_N = 230$ V		
Nominal speed N_n [min ⁻¹]	4000	8000
Rated torque M_n [Nm]	0.50	0.50
Rated output P_n [kW]	0.21	0.42
Power supply $U_N = 480$ V		
Nominal speed N_n [min ⁻¹]	9000	
Rated torque M_n [Nm]	0.50	0.50
Rated output P_n [kW]	0.47	0.47
Connection technology	iTec	
Reference flange aluminum 230 mm x 130 mm x 10 mm		



Feedback system:

- Single turn, absolut turn, resolution 18 bits, accuracy 0.03° (other options available)
- Cable: one cable technology

Note the rated performance based on the power supply voltage

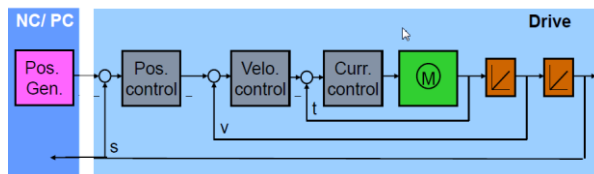
https://download.beckhoff.com/download/Document/motion/am8000_am8500_ba_en.pdf

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Case Study: Beckhoff AX5103 Servo Drive

Servo Drive AX5103

- Control of torque (current), velocity and position



EtherCAT (minimum)	Position loop	Speed loop	Current loop	IGBT switching	Motor cable
31.25 μs	125 μs	125 μs	31.25 μs	16 kHz	32 kHz
62.5 μs	125 μs	125 μs	62.5 μs	8 kHz	16 kHz
62.5 μs	125 μs	125 μs	125 μs	4 kHz	8 kHz



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Case Study: Beckhoff AX5103 Servo Drive with AM8021 Servomotor

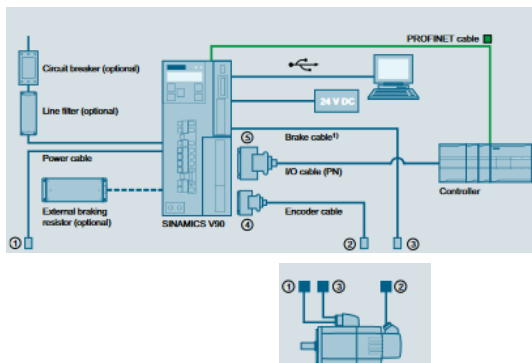


Note the rated performance based on the power supply voltage

<https://www.beckhoff.com/en-en/products/motion/rotary-servomotors/am8000-servomotors/am8021-wbyz.html>

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Case Study: Siemens Servomotor and Servo Drive



Sinamics V90

Siemens



Simotics A1FL6

https://cache.industry.siemens.com/dl/files/233/109758233/att_1096132/v1/motion-control-drives-D33-complete-English-2019-05-Update-2022-02.pdf?download=true

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Case study: Omron Servomotor and Servo Drive

OMRON AC servo drive with built-in Ether CAT and safety functions
Servo drive R88D-1S and AC servomotor series R88M

Power range from 200 W to 3 kW

- 20 bit high-resolution encoder
- 350% momentary maximum torque (200 V, 750 W max.)
- Battery-free absolute multi-turn encoder
- Safety over Ether CAT (FSoE)

Safety functions incorporated:

STO SS1 SS2 SOS SLS SLP SDI SBC (PLe SIL3) with FSoE



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<https://www.motioncontroltips.com/faq-what-are-typical-drive-based-safety-functions/>

Final Summary: Servomotor PMSM

Summary of main characteristics of PMSM

- Electronic commutation, eliminating the need for brushes
- No periodic maintenance required due to the brushless design
- Low rotor inertia, thanks to the permanent-magnet rotor construction
- Improved cooling capability through easier ventilation
- High efficiency across a wide operating range
- Capability to achieve high rotational speeds
- Strong performance at low speeds, with smooth torque delivery
- Standstill (holding) torque available, enabling precise positioning
- The Torque is directly proportional to the motor current ($T = K_t \cdot I$)

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Final Summary: Servo Drive

Summary of main characteristics of Servo Drive

- Serves as the power supply for the servomotor
- Includes the appropriate interfaces for the rotor position transducer (encoder/resolver) and the motor brake
- Uses rotor position feedback to determine the correct power required for the stator windings, enabling precise torque, speed, or position control
- Can be powered by DC or AC (single-phase or three-phase) sources
- Provides digital inputs and outputs for auxiliary functions and safety devices
- Offers discrete inputs or network communication interfaces for control
- Includes built-in safety functions
- Additional features are available depending on the model

Linear Servomotors (LSM)

Contents

- Introduction to direct-drive linear motion
- Core electromagnetic topologies
- Mechanical & kinematic principles
- Linear motor dynamic performance
- Feedback and sensing architecture
- Vector control in linear motors
- Comparison with ball-screw systems
- Industrial examples and case studies

Introduction to Linear Servomotors

The Direct-Drive Paradigm

Traditional systems used mechanical transmissions (ball screws, belt drives, gears) to convert rotary motion into linear motion

A **linear servomotor (LSM)** eliminates this stage:

- No intermediate mechanics
- Electromagnetic force applied directly to the moving load
- Higher precision and bandwidth

The “Unrolled PMSM” Concept

A linear motor can be visualized as a **PMSM** cut open and unrolled:

- Rotary PMSM → rotating field
- Linear PMSM → traveling magnetic field along a track
- The moving part (forcer) follows the field to produce force

Advantages of Direct-Drive Linear Motion

Removal of the mechanical chain eliminates:

- **Backlash** (gears/screw play)
- **Elasticity and compliance** (screw wind-up, belt stretch)
- **Friction losses**
- **Mechanical wear**

Benefits

- High mechanical stiffness
- Accuracy is limited mainly by encoder resolution
- Fast response and superior dynamic performance

Electromagnetic Force Production

Linear motors generate force using the Lorentz Force law

Thrust Force Equation

$$F_{thrust} = K_f \cdot I \cdot L \sin(\theta)$$

where:

- K_f is the motor-specific Force Constant (analogous to K_f in rotary motors)
- I is the current in the coils
- L is the length of the conductor in the magnetic field
- θ is the electrical phase angle (kept near 90° by FOC for maximum force)

Vector Control (FOC) ensures:

- Maximized thrust
- Smooth force ripple
- Precise control at all speeds

Dynamic Performance of Linear Servomotors

Linear motors offer performance levels not possible with ball screws

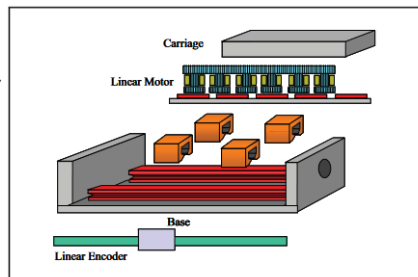
- Velocity: up to 10 - 15 m/s
- Acceleration: 10 g to 30 g (low moving mass)
- Dynamic bandwidth: 50 -100 Hz (vs. 5 -15 Hz for screws)
- High positioning accuracy (limited mainly by encoder resolution)

Precision Table Example

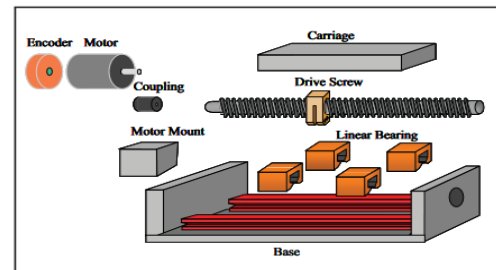
Linear motor vs. Ball-screw table

- Fewer components → compact construction
- No backlash → improved accuracy
- Higher dynamics (velocity and acceleration)
- Ideal for precision machinery

Precision table with linear motor



Precision table with ball screw drive



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Linear Servomotor: Main Elements

Core elements

- Coils
- Permanent magnets tracks
- A linear encoder and a linear guide (not always included with the motor)
- Servo drive with FOC (similar to the ones used with rotary PMSM)

Main Topologies of linear servomotors (LSM)

1. Iron-core
2. Ironless
3. Slotless
4. Tubular

With linear Servomotors , the motor elements (coils + PM tracks + Linear guide), and feedback transducer, are not integrated into a single hardware component

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Integrated measuring systems for linear axis

Integrated Measuring Systems (IMS) provide a **direct measurement** solution by embedding the transducer directly into the linear guide components

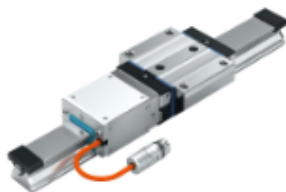
■ Key Advantages

- **Direct sensing** of the carriage position removes transmission errors
- **Compact Integration:** the sensor is built into the runner block, requiring no additional mounting space
- **Harsh Environment Suitability:** utilizing inductive or magnetic principles makes these systems resistant to coolant, dust, and magnetic interference
- **Scalability:** applicable to **linear motors**, machine tools, and high-speed pick-and-place robots

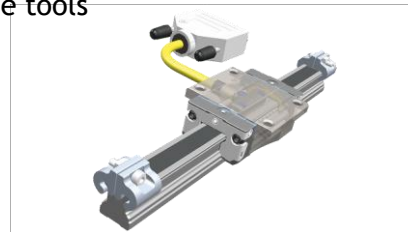
Integrated measuring systems for linear axis

Example of systems from Boschrexroth

- Working principle: **inductive or magnetic**
- **Incremental or absolute systems** variants
- Applicable to **linear motors** and machine tools



IMS (inductive)
catalogue



IMSCoMpaCt (magnetic)
catalogue

Integrated measuring systems for linear axis

Working Principles

The IMS consists of two primary components: the **Scale (Ruler)** and the **Sensing Head**

- **Sensing Technology**
 - **Inductive Systems (e.g., Bosch Rexroth IMS):** high precision, immune to external magnetic fields, and highly durable
 - **Magnetic Systems (e.g., IMSCompact):** cost-effective, compact, and suitable for applications with slightly lower precision requirements
- **Physical Architecture**
 - **The Ruler (Scale):** a precision-graduated track fixed directly to the linear rail
 - **The Head:** an electronic sensing unit integrated into the runner block (the moving part)
 - **The Reference Mark:** integrated into the scale to allow for absolute zeroing of the axis

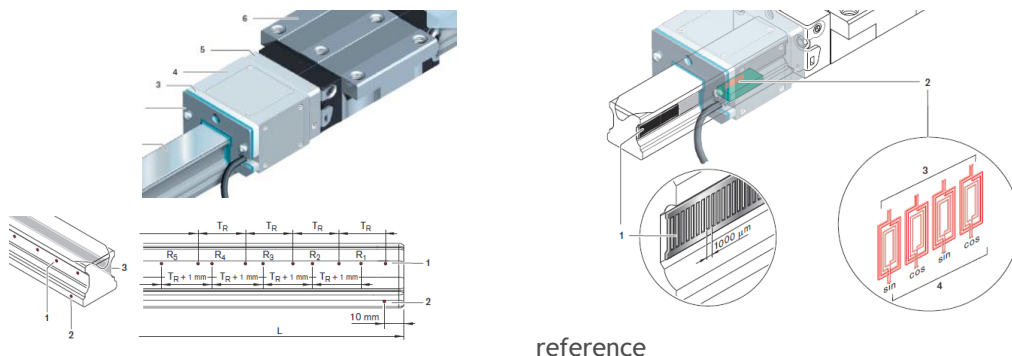
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Integrated measuring systems for linear axis

Roller rail system with integrated position measurement system

- Head (the running block) and linear scale (fixed to the rail)



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Integrated measuring systems for linear axis

Signal Processing and Evaluation

The sensing head generates analog signals that are then processed into high-resolution digital data for the servo drive

- **Analog Signal Output**

The raw output consists of two sinusoidal voltage signals (U_{sin}) and (U_{cos}) with a typical period (scale pitch) of $1000 \mu m$. These signals are out of phase by 90° , allowing for direction sensing

Signal Amplitude: is typically $1 V_{pp}$ (peak-to-peak)

Center Voltage (U_0): usually $2.5 V \pm 0.5 V$

- **Digital Resolution and Interpolation**

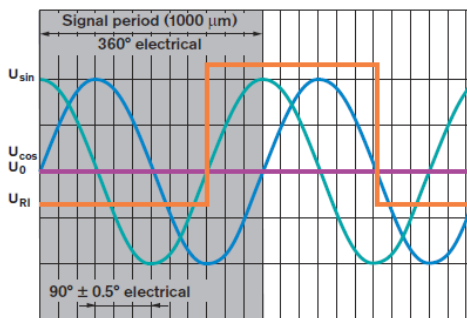
The final system resolution is calculated by dividing the scale pitch by an evaluation factor (interpolation). This process takes the analog sine wave and "slices" it into thousands of digital increments

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Integrated measuring systems for linear axis

Electronics can provide an analog output signal and digital outputs (encoder type)



U_{sin}/U_{cos} Sinusoidal voltage signals
 U_0 Passage through zero
 $U_0 = 2.5 V \pm 0.5 V$
 U_{RI} Reference mark signal

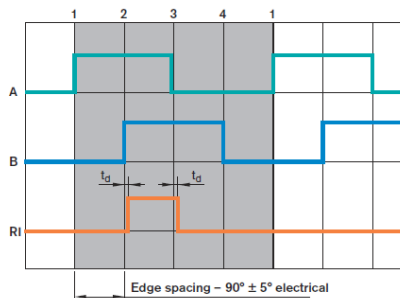
$$\text{Resolution} = \frac{\text{scale pitch}}{\text{evaluation} \cdot \text{factor}}$$

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Integrated measuring systems for linear axis

- After interpolation, the measurement system provides digital outputs (square wave, TTL levels). Possible resolutions are 0.25 μm , 1 μm , 5 μm and 10 μm .
- The interpolation accuracy is identical for all resolutions and is ± 3 micron
- The repeatability of the position measurement is dependent on the chosen resolution:

Resolution with TTL signal	μm	0.25	1	5	10
Repeatability	μm	2	2	5	10



A/B Incremental TTL square-wave signals
 RI Reference mark signals
 t_d Time delay $|t_d| < 0.1 \mu\text{s}$

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Iron-Core Linear Motors

1. Iron-core motors consist of aforcer that rides over a single magnet rail. The forcer is made of copper windings wrapped around iron laminations

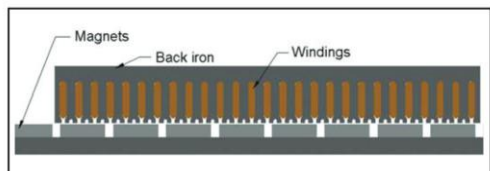


Image from: Parker Hannifin Corporation



Parker R7 Iron-core Linear Motor

Advantages

- High force density
- High thermal dissipation
- Lower cost

Disadvantages

- Highly attractive force (5 to 13 times greater than the force generated)
- Cogging (Reluctance effects) - limits the smoothness of motion and creates velocity ripple

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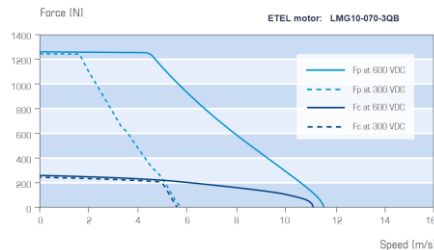
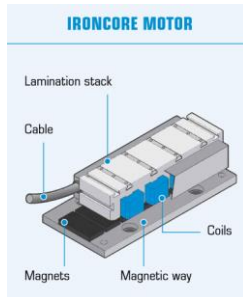
Iron-Core Example Series (Etel)

Typical specifications (Etel)

- Force range: 67-689 N continuous
- Peak forces up to 3700 N
- Speed up to 15 m/s
- Available in multiple lengths



Etel LMG10-070-3QB



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[Etel reference book](#)

www.etel.ch/linear-motors/

Ironless Linear Motors

2. Ironless motors consist of aforcer that rides between dual magnet rails (known as “aircore” or “U-channel” motors). No iron laminations in the coils

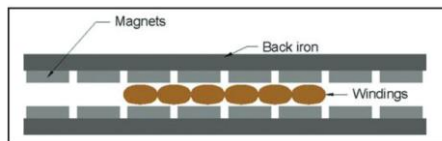


Image from: Parker Hannifin Corporation



Parker ML50 Ironless Linear Motor

Advantages

- No attractive force - balanced dual magnet track
- No cogging - ironless forcer for zero cogging and ultimate smoothness
- Low moving mass
- Very smooth motion

Disadvantages

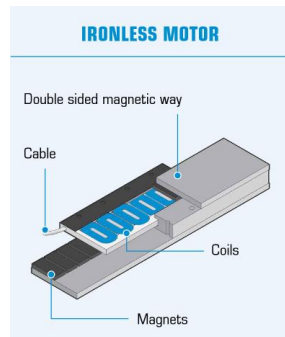
- Poor heat dissipation
- Lower force per size, when compared to iron-core designs
- Higher cost (dual magnet track)

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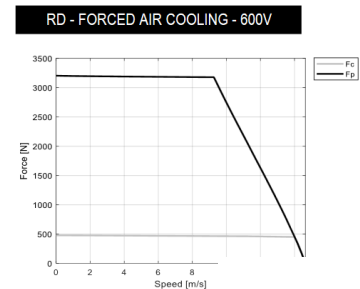
Ironless Example Series (ETEL)

Typical specifications (Etel)

- Continuous force up to 478 N
- Peak force up to 3200 N
- Moving mass as low as 0.1 kg



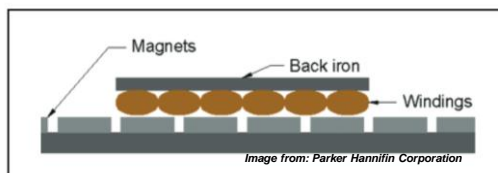
Etel ILM+12-060



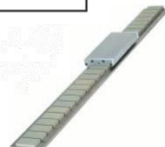
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Slotless Linear Motors

3. Slotless Motors are a Hybrid design between iron-core and ironless topologies



Parker 406LXR Slotless Linear Motor Driven, Dual Square Rail Guided Linear Positioners



Advantages

- Lower cost than ironless (single magnet rail)
- Better heat dissipation (compared to ironless design)
- More force per package size (compared to ironless design)
- Lighter weight and lower inertia forcer (compared to iron-core design)
- Less cogging (compared to iron core designs)

Disadvantages

- Some attractive force and cogging
- The air gap is critical
- Less efficient than both iron-core and ironless

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Slotless Linear Motor Positioner Example

- Parker slotless positioner Parker 406LXR



Recommended servo drive
Parker Compax3 - servo drive

- 1 Pass-through cabling
- 2 Connection panel
- 3 High strength extruded aluminum body
- 4 Magnet rail
- 5 Slotless linear motor
- 6 Linear guidance system
- 7 Integral linear encoder
- 8 Home/limit sensors
- 9 "Quick change" cabling
- 10 Protective seals

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Slotless Positioner Configurations

Parker 406LXR slotless linear motor positioner

Multiple configurations:

- Frame width of 150 mm
- Fifteen standard strokes available from 50 to 1950 mm
- Positional repeatability of +/- 1.0 micron
- Optical encoder resolutions of 5.0, 1.0, 0.5, and 0.1 micron as well as a Sine output
- Maximum velocity of 3000 mm/sec
- Integrated 8 or 12 pole linear motor, home/limit sensor and feedback
- Maximum payload of 1766 N
- Maximum thrust of 330 N
- Pre-configured cable options
- IP30 rating
- Standard multi-axis systems
- Convenient tapped hole mounting
- Laser test data with slope correction values with each precision grade stage



406LXR Series Product Manual

Model Motor	406LXR 8 Pole	406LXR 12 Pole
Rated Load kg	180	180
Maximum Acceleration	5 Gs	
Maximum Velocity m/s		
Encoder Resolution	0.1µm	0.3
	0.5µm	1.5
	1.0µm	3.0
	5.0µm	3.0
Sine Output	3.0	
Positional Repeatability		
Encoder Resolution	0.1µm	±1.0µm
	0.5µm	±1.0µm
	1.0µm	±2.0µm
	5.0µm	±10.0µm
Sine Output	(interpolation dependant)	
Maximum Peak Force N (lb)	225 (50)	330 (75)
Maximum Peak Force N (lb)	75 (17)	110 (25)
Carriage Weight kg	3.2	4.1

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Slotless XY Stage Example

Parker 406LXR slotless linear motor positioner

LXR Series Technical Data

Frame size	Unit	406LXR	
		8-pole	12-pole
Motor			
Continuous Force	[N]	75	110
Peak force	[N]	225	330
Continuous current at 230 VAC	[A]	2.470	2.400
Peak current*	[A]	7.3	7.1
Force constant	[N/A]	30.619	46.54
Nominal load	[kg]	180	180
Maximum velocity			
Feedback resolution 0.1 µm		0.3	0.3
Feedback resolution 0.5 µm	[m/s]	1.5	1.5
Feedback resolution 1.0 µm		3.0	3.0
Feedback resolution 5.0 µm		3.0	3.0
Sine - Cosine		3.0	3.0
Maximum acceleration	[m/s ²]	49	
Positional Repeatability			
Feedback resolution 0.1 µm		± 1.0	
Feedback resolution 0.5 µm	[µm]	± 1.0	
Feedback resolution 1.0 µm		± 2.0	
Feedback resolution 5.0 µm		± 10.0	
Sine - Cosine		(Interpolation dependent)	
Carriage mass	[kg]	3.2	4.1

* based on a winding temperature of up to 60 °C for a period of:
 404LXR - 5 s, 406LXR - 3 s, 412LXR - 63 s



Two axes configuration with precise orthogonal mounting

[LXR series catalogue](#)

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Tubular Linear Motors

4. Tubular linear servomotor

Construction

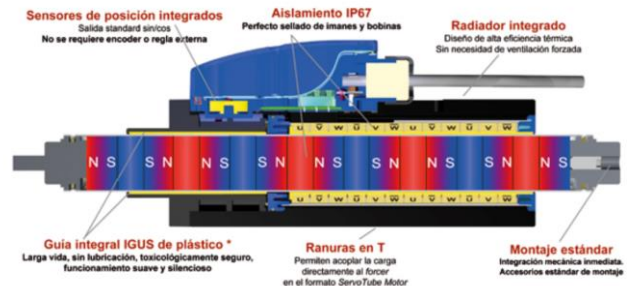
- Cylindrical magnet rod
- Coils wrapped around the rod
- Completely symmetric air gap

Advantages

- Zero net attractive force
- High force density
- Very good thermal efficiency
- Good environmental sealing

Disadvantages

- Stroke limited by rod deflection
- Mechanical support structure required
- Inertia Constraints (the moving part often contains magnets and is heavier than air-core motor)
- Maintenance of Air Gap



*Tubular motor ServoTube STA2506
 from [Copley Controls](#)*

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Tubular Motor Examples

4. Tubular linear servomotor



LinMot
 Model P10



Dunkermotoren
 MODEL STA2504



Faulhaber Linear DC
 servomotor

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Topology Comparison

Feature	Iron-Core	Slotless	Ironless	Tubular
Force Density	Highest	Medium	Lowest	High
Smoothness (Cogging)	High Cogging	Very Low	Zero	Very Low
Attractive Force	Very High	Moderate	Zero	Zero
Heat Dissipation	Excellent	Moderate	Poor	High
Inductance	High	Low	Very Low	Moderate
Typical Application	Machining	High-speed packaging	Semiconductors	Pneumatic replacement

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Beckhoff Linear Servomotors Overview

- Tubular motors (AA2500 series)
- Iron-core AL8000 series and AL2000 series
- Electric cylinder (AA3000 series and AA3100 series)
- Linear actuator with integrated power electronics (AA1000 series)

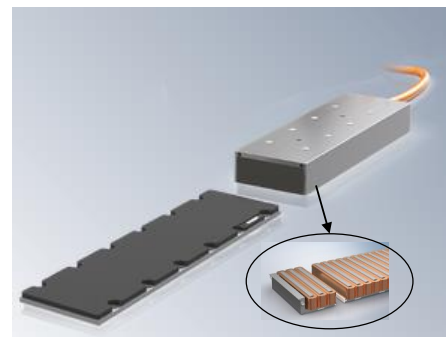


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Beckhoff AL8000 Iron-Core Motors

Iron-core (AL8000 series)

- Modular concept: magnetic plate + coil (secondary)
- External guide and encoder not included
- Continuous /Peak force up to 3000 /6750 N (AL806F)
- Velocities up to 12 m/s (AL8021), 6 m/s (AL806F)
- Accelerations up to 30g
- Cooling: convection or water (AL806F)
- Servo drive recommended AX8000 or AX5000

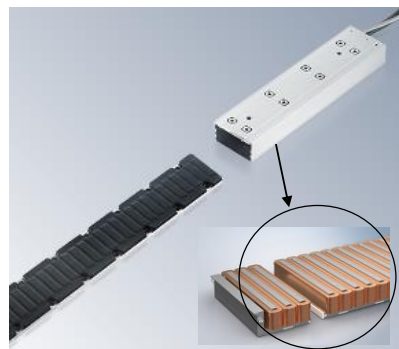


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Beckhoff AL2000 Iron-Core Motors

Iron-core (AL2000 series)

- External guide and encoder not included
- Continuous /Peak force up to 2000 /4500 N
- Velocities up to 10 m/s
- Cooling: convection or water (AL806N)
- Accelerations up to 30g
- Guiding and encoder not included
- Servo drive recommended [AX5000](#)

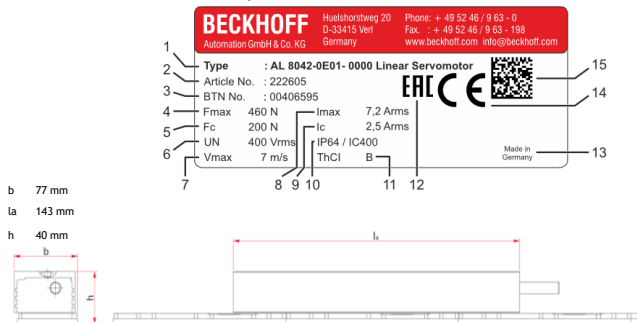


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Beckhoff AL8042 Motor Details

Beckhoff linear servomotor

Name plate of AL8042 linear servomotor

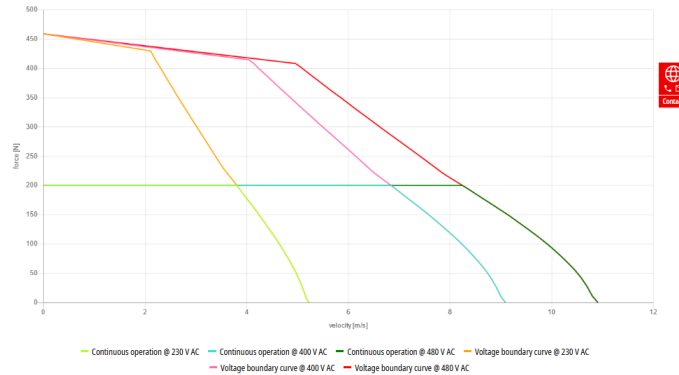


- 1 Article description
- 2 Order number
- 3 Beckhoff traceability number
- 4 Peak force
- 5 Continuous force
- 6 Nominal voltage
- 7 Maximum velocity
- 8 Peak current
- 9 Continuous current
- 10 Protection class
- 11 Insulation class
- 12 EAC approval
- 13 Country of manufacture
- 14 CE conformity
- 15 Data matrix code; BIC = Be

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Beckhoff AL8042 Force-Speed Curve

Force-speed curve for AL8042 linear servomotor

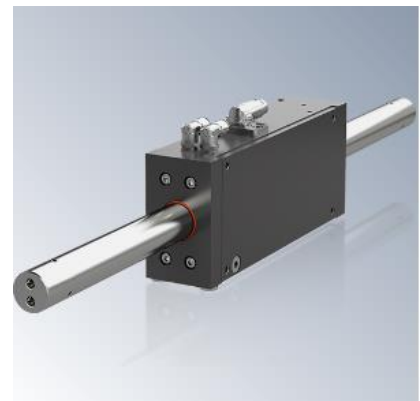


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Beckhoff AA2500 Tubular Motors

Tubular motors (AA2500 series)

- Ironless motor
- Magnetic rod is available in different lengths (travel path of up to 600 mm)
- Continuous / peak force 370 N / 1050 N
- Max speed 8 m/s
- Water cooling
- Servo drive recommended AX8000 or AX5000 series

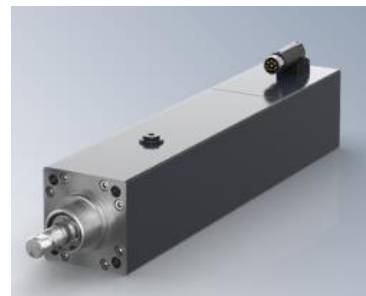


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Beckhoff AA3000 Electric Cylinder

Electric cylinder (AA3000 series)

- based on the AM8000 iron-core drive technology
- compact dimensions thanks to fully integrated mechanism
- simple conversion of pneumatic applications due to compatibility with ISO 15552
- combines the force, dynamics and compactness of pneumatics with the controllability and efficiency of an electric servo drive
- 24-bit multi-turn encoder
- travel path of 150, 200 and 250 mm
- Compatible servo drive [AX8000](#) or [AX5000](#)

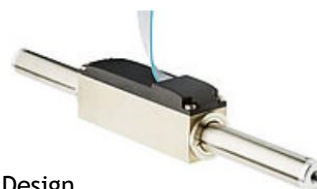
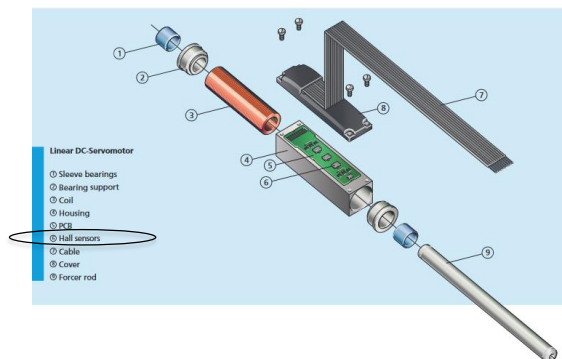


Product variants	Peak force	Continuous force	Max. speed	Max. acceleration
AA3023-22Hz	6250 N	1400 N	0.50 m/s	10 m/s ²
AA3023-42Hz	3125 N	700 N	1.0 m/s	20 m/s ²
AA3053-44Hz	25,000 N	6350 N	0.50 m/s	10 m/s ²
AA3053-64Hz	12,500 N	3175 N	1.0 m/s	20 m/s ²

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Faulhaber Tubular Linear DC Motor

Faulhaber



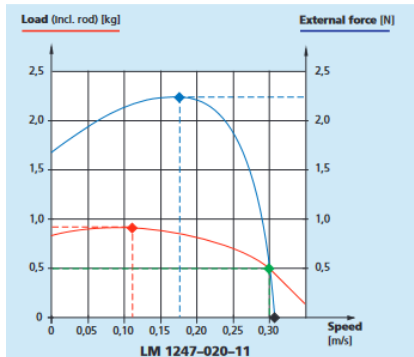
Design

- 3-phase self-supporting coil
- Non-magnetic metal housing
- Forcer rod with magnets
- Built-in Hall sensors
- Suitable for micro-positioning applications

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Faulhaber Tubular Linear DC Motor

Faulhaber linear DC servomotor: tubular



LM	Linear Motor
12	Motor width \square [mm]
47	Motor length [mm]
020	Stroke length [mm]
11	Sensors type: linear

LM1247-020-11

Load curve

Allows knowing the maximum applicable load (incl. rod) for a given speed with 0 N external force. The graph shows that a maximum load (incl. rod) (♦) of 0,87 kg can be applied at a speed of 0,11 m/s.

External force curve

Allows knowing the maximum applicable external force for a given speed with a load of 0,5 kg. The graph shows that the max. achievable speed (♦) without external forces, but with a load of 0,5 kg is 0,31 m/s. Therefore, the maximum applicable external force (♦) at a speed of 0,3 m/s is 0,5 N. The external peak force (♦) is achieved at a speed of 0,17 m/s, corresponding to a maximum applicable external force of 2,27 N.

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Omron Linear Motors

Omron linear motors:

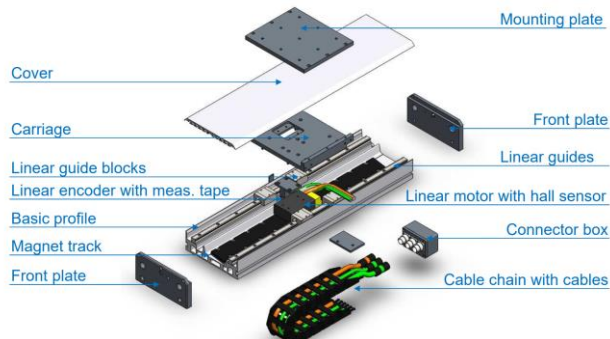
- iron-core (FW) and
- ironless (GW) motors
- Necessary to provide an exterior guide system and position transducer (encoder)
- Compatible servo drive: Accurax G5

Product	Accurax FW	Accurax GW
Rated force range	Up to 760 N	Up to 423 N
<input type="checkbox"/> Up to 423 N (1) <input type="checkbox"/> Up to 760 N (1)		
Peak force range	105 N to 2,000 N	100 N to 2,100 N
<input type="checkbox"/> 100 N to 2,100 N (1) <input type="checkbox"/> 105 N to 2,000 N (1)		
Maximum Speed	10 m/sec	16 m/sec
<input type="checkbox"/> 10 m/sec (1) <input type="checkbox"/> 16 m/sec (1)		

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Omron Linear Axis Example

Linear Axis (Cartesian) - Accurax, from Omron



Compatible servo drive: Accurax G5



R88L-EA-AF- Accurax Linear Motor Axis

Iron-core linear motor
 Up to 5 m/s maximum speed with 1 mm repeatability
 Ratings: 230/400 VAC, 48 up to 760 N (2000 N peak force)

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Final Summary: Linear Servomotors

Summary of main characteristics

- **Direct-drive linear motion** with no mechanical transmission elements
- **High dynamic performance**, typically up to 50 Hz (compared with 5-15 Hz for ball-screw systems)
- **Wide force-speed operating range**, enabling velocities up to 15 m/s and accelerations up to 5 g
- **High force capability at low or zero speed**, allowing precise holding forces without mechanical backlash ($F = K_f \cdot I$)
- **Frameless linear motors** are supplied without housing, linear guides, or feedback systems, providing greater design flexibility for machine builders but requiring additional integration effort
- **No mechanical brakes** are inherently available in direct-drive solutions
- **Typical applications:** CNC equipment, semiconductor manufacturing machines, packaging systems, test equipment, precision positioning tables, and other high-performance automation systems

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