Gearmotors \ Industrial Gear Units \ Drive Electronics \ Drive Automation \ Services

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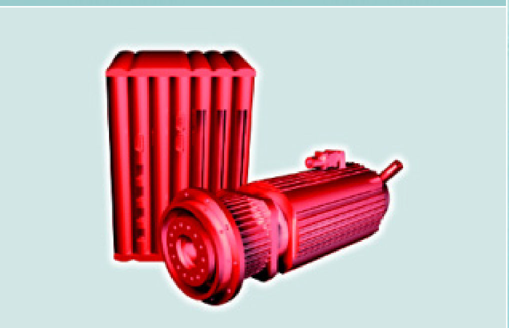
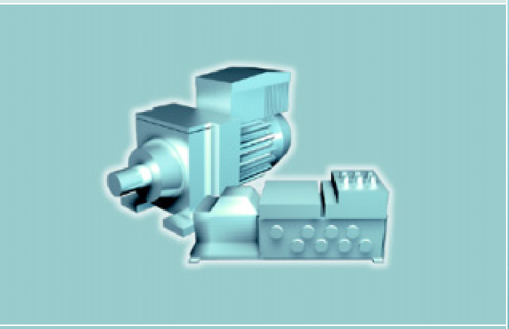
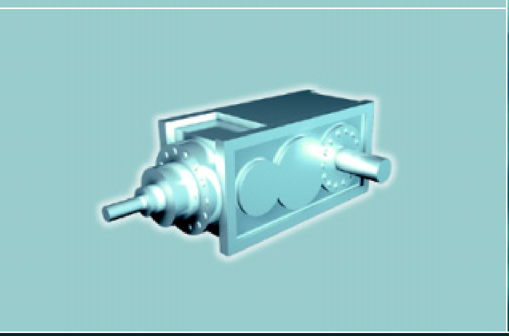
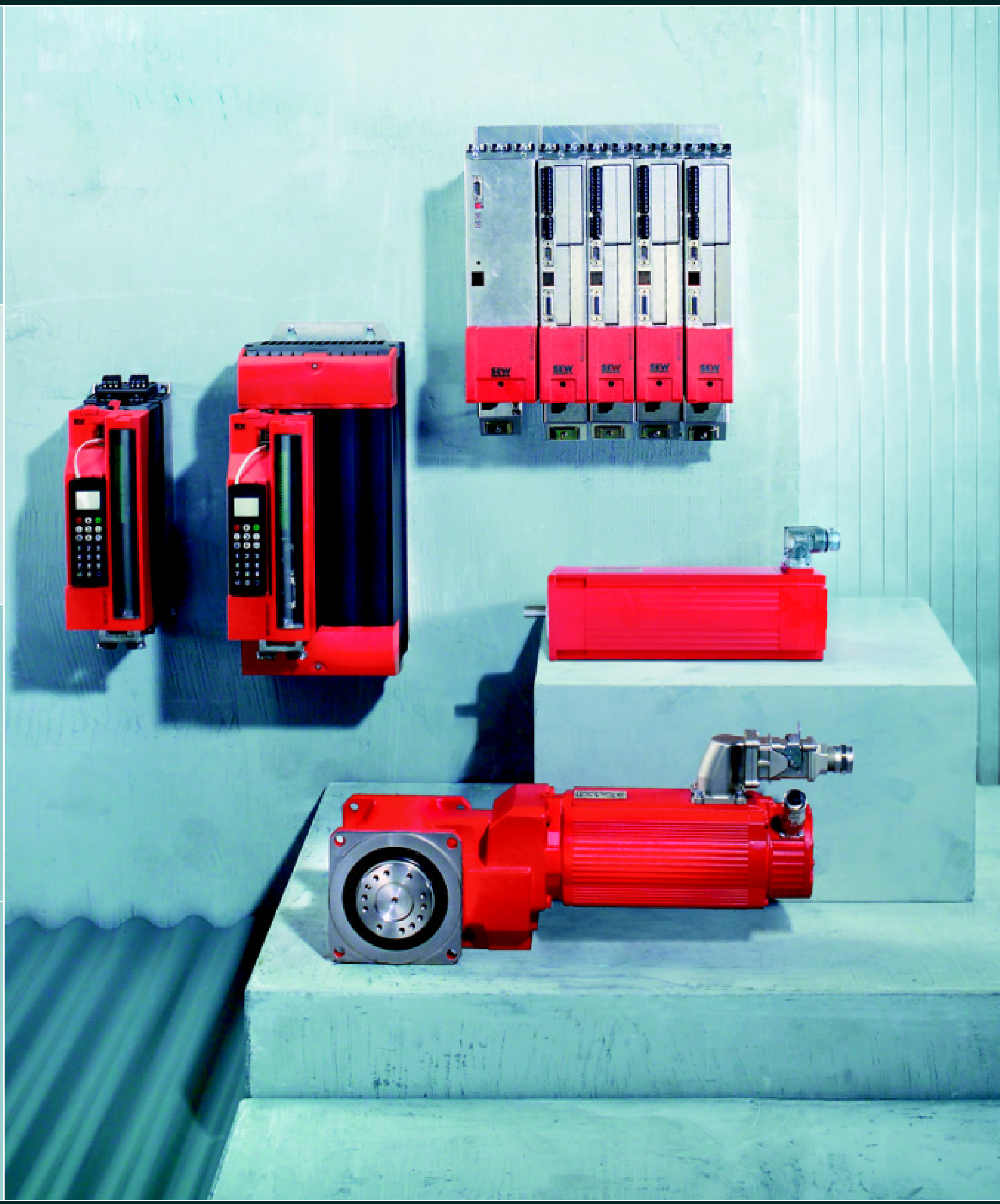

Drive Engineering – Practical Implementation

Servo Technology

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Edition 09/2006

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1 Introduction

SEW-EURODRIVE is one of the leading companies in the world market for electrical drive engineering. The company headquarters are in Bruchsal, Germany. Components for the SEW-EURODRIVE modular drive system are manufactured to the highest quality standards in production plants located in Germany, France, Finland, the United States, Brazil and China. The individual drive systems are assembled with a consistently high quality standard and very short delivery times from stocked components in 61 assembly plants located in 44 industrialized countries all over the world. SEW-EURODRIVE sales, consulting, customer and spare parts services are available in more than 60 countries around the globe.

Its global presence, extensive product range and broad spectrum of services make SEW-EURODRIVE the ideal partner for demanding automation solutions.

Especially the area of servo technology has developed into a strong growth sector with a high innovation rate. SEW-EURODRIVE stays abreast of this dynamic market situation with market-driven product development.

The volume before you from the series "Drive Engineering – Practical Implementation" is aimed at technical specialists that process servo applications and provides clear information on the design and theory of operation of common components of servo technology as well as their applications and project planning.

SEW-EURODRIVE – Driving the world.

Bruchsal, September 2006

1.1 Definition and development of servo technology

The word "servo" is derived from the Latin "servus" and means slave, servant, or helper. This word was appropriate when servo drives were only used as auxiliary drives for secondary tasks such as drives for infrequent speed variations in machine tools. This limited use was due to inefficient linear amplifiers and limited voltage of approximately 200 V between the segments of the commutators of DC machines. The drives were controlled via analog means, which greatly restricted the range of functions and required a great deal of effort for any additional features.

The key to the success of today's servo technology was the rapid development in the area of semiconductor technology and modern microcontrollers. Highly integrated and powerful computer systems and their memory modules now make the use of digital controls possible, allowing the range of functions for the drive systems to be considerably increased.

Because of this development, modern servo systems are being used more and more as main drives and less and less for secondary tasks.

1.2 Areas of application for servo technology

The increasing automation in all areas of mechanical engineering and system design requires shorter and shorter cycle times and more flexibility when changing products. These requirements are becoming increasingly more difficult to implement with conventional asynchronous systems or hydraulic or pneumatic components. This development has caused to a big change in drive engineering, leading to the use of today's servo drives:

- Synchronous servomotors
- Asynchronous servomotors
- Synchronous linear motors

This volume covers drive systems with the servomotors listed above.

These drives are used primarily in the following industries:

- Packaging technology
- Robotics
- Machine tools
- Handling systems
- Sheet metal processing
- Paper processing
- Materials handling

1.3 Components of a servo system

Due to the increasing requirements of mechanical engineering and system design regarding cycle and change-over times, modern servo systems consist of much more than just a servomotor and a servo inverter. This fact places higher requirements on functions and interfaces of the machine controls, especially in drive engineering.

Components of the SEW servo systems MOVIDRIVE® and MOVIAXIS®

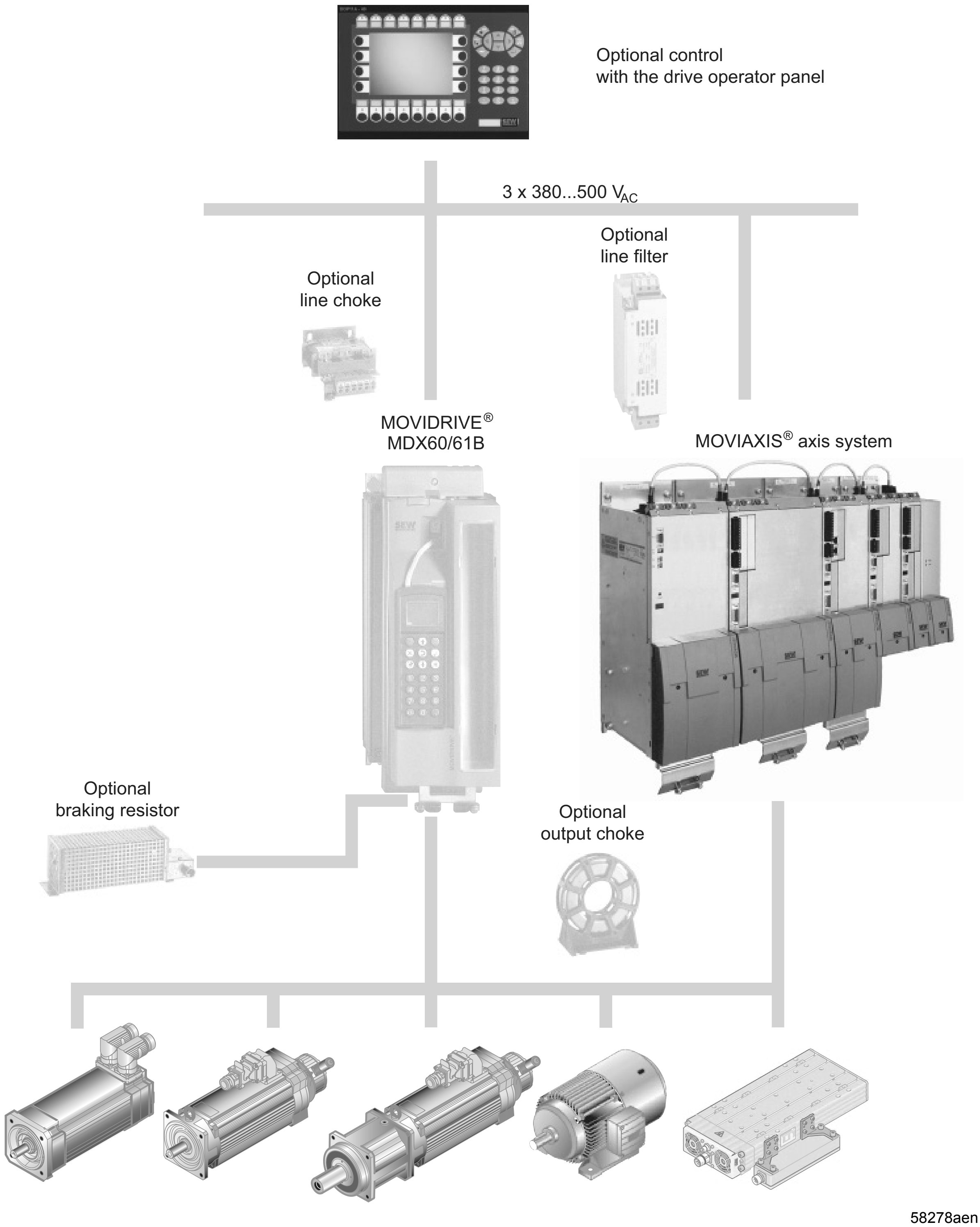

Fig. 1: Components of a servo system

Components of a servo system (see Fig. 1)

1. Control (optional): Modern and powerful servo inverters such as MOVIDRIVE® and MOVIAXIS® can be programmed, allowing them control even demanding technologies such as phase-synchronous operation and electronic cams Additionally, it is possible to build a control board into a servo inverter to some extent for axis coordination and classical PLC functionality.
2. MOVIDRIVE® single-axis inverter
3. MOVIAXIS® multi-axis servo inverter
4. CMP synchronous servomotor
5. CM synchronous servomotor with planetary gear unit
6. CT/CV asynchronous servomotor
7. SL2 synchronous linear motor

Additional components of a servo system

- Prefabricated motor and encoder cables
- Line choke/line filter; depends on servo inverter and EMC limit value class
- Braking resistors
- Regenerative power supply module
- Fieldbus interface; optional as it depends on the application any existing machine control
- Switched-mode power supplies

2 Servomotors

Features of a servomotor

Servomotors are motors that exhibit the following in a wide speed range:

- High dynamics
- High positioning accuracy
- High overload capacity

Additional features of servomotors are:

- High speed accuracy
- Large speed setting range
- Short acceleration time
- Short torque rise time
- High static torque
- Small mass moment of inertia
- Low weight
- Compact design

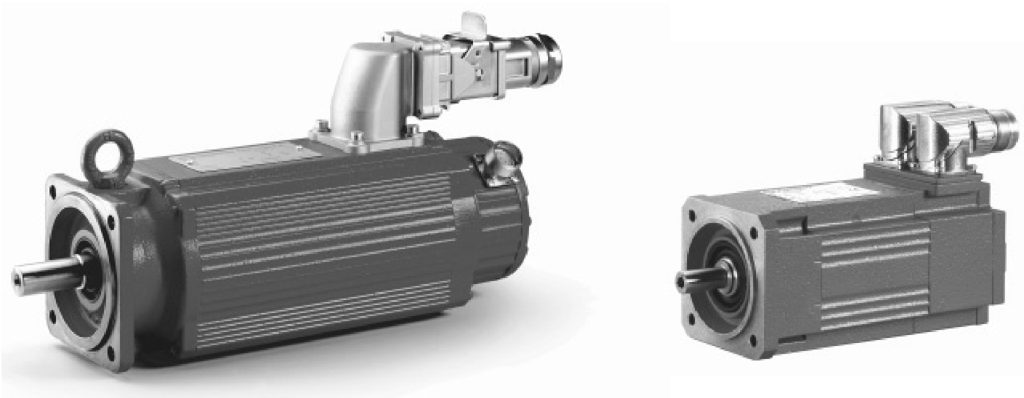

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Fig. 2: Example of SEW servomotors of the CM.. and CMP.. series

Basic design

The basic design of a servomotor consists of:

- A rotor
- A stator
- The power connection; designed as a connector or terminal box
- A feedback system with connection

2.1 Overview of common servomotors

The servomotor family can be grouped as follows:

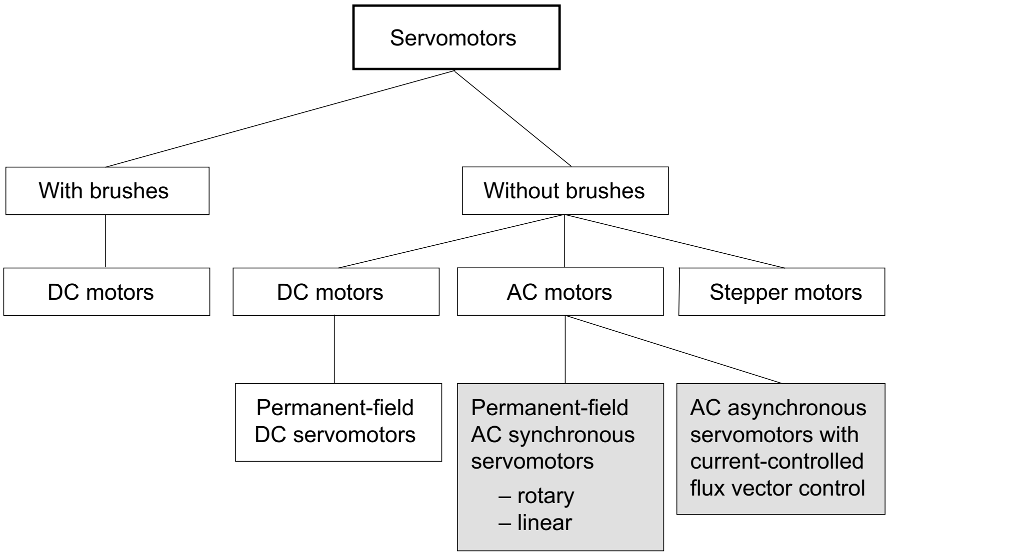

Fig. 3: Overview of servomotors

The most important differentiating criteria lie in:

- The design of the motors (stator, rotor)
- The necessary control structures
- The encoder systems

Up until a few years ago, brushless, permanent-field DC motors were used as servo drives, which were controlled by thyristor controllers or transistor chopper converters.

The technical advances in the area of power semiconductors and microcontrollers caused the use of synchronous servomotors to increase steadily in the nineties.

Today, permanent-field AC synchronous servomotors have a larger market share than AC asynchronous servomotors. This is because of the properties of the motors.

The permanent-field AC synchronous servomotors and the AC asynchronous servomotors will be looked at in more detail below.

Terms and definitions

The motors are designated as follows in this publication:

- **Synchronous servomotor** ≙ Permanent-field AC synchronous motor
- **Asynchronous servomotor** ≙ AC asynchronous servomotor
- **Synchronous linear motor** ≙ Permanent-field AC linear synchronous motor

2.2 *Features of synchronous and asynchronous servomotors*

Features of synchronous servomotors
High dynamics
Moderately good control characteristics for large masses
High overload capacity, up to 6 x
High thermal continuous load capacity throughout the entire speed range
Heat dissipation via convection, heat transmission and emission
High speed quality
Static torque continuously available
High speed setting range, 1:5000
Torque ripple (cogging) at low speeds. See also the definition on page 89.

Features of asynchronous servomotors
Moderate to high dynamics
Good control characteristics for large external masses
High overload capacity, up to 3 x
High thermal continuous load capacity; depending on speed
Heat dissipation via fans
High speed quality
Due to thermal load in the lower speed range that is too high, torque cannot be available continuously without a forced cooling fan
High speed setting range, 1:5000
Almost no torque ripple (cogging). See also the definition on page 89.

2.3 Design of synchronous servomotors

Basic design

The basic design of a synchronous servomotor consists of:

- A rotor with permanent magnets
- A stator with suitable winding
- The power connection; designed as a connector or terminal box
- An encoder

Different versions

There are two kinds of synchronous servomotors:

- With housing
- Without housing

Without housing means that the laminated core of the stator forms the body of the motor. This allows the use of the entire iron cross section.

In the following, you will find descriptions of both designs using SEW motors:

- Without housing. CMP motor
- With housing: CM/DS motor
- Without housing: CMD motor

2.3.1 Design of the CMP motor

CMP servomotors feature extremely high dynamic properties, low mass inertia, a compact design, and high power density.

CMP servomotors are motors with housing.

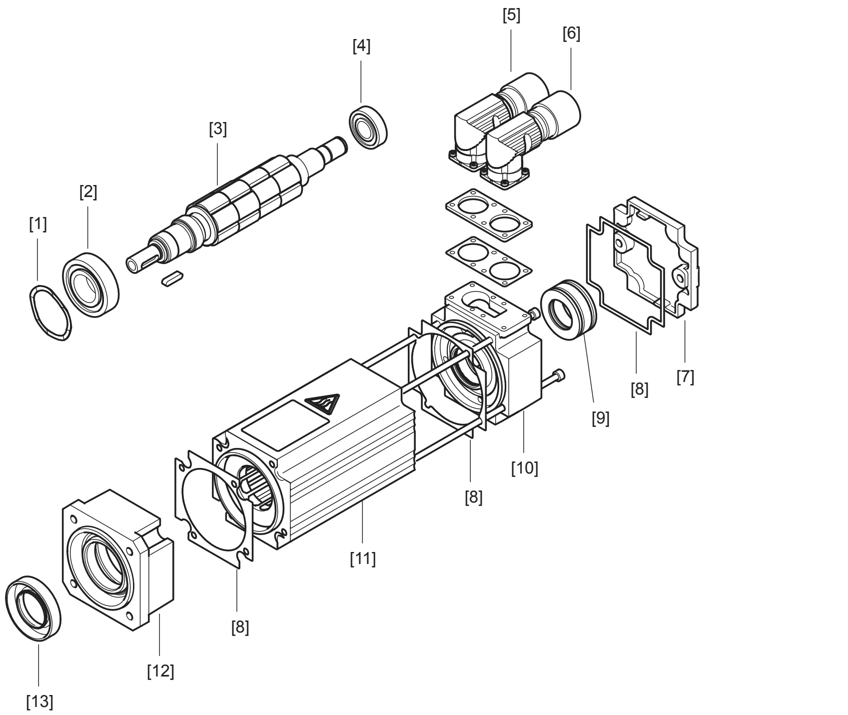

Fig. 4: Design of the SEW-EURODRIVE CMP synchronous servomotor

[1]	Equalizing ring	[8]	Flat gasket
[2]	Grooved ball bearing	[9]	Resolver
[3]	Rotor	[10]	Non drive-end bearing shield
[4]	Grooved ball bearing	[11]	Housing with stator
[5]	SM/SB signal plug connector	[12]	Flanged end shield
[6]	SM/SB power plug connector	[13]	Oil seal
[7]	Housing cover		

Features and options of the CMP motor

- Up to 4.5 x overload capacity
- Stator with single-tooth winding
- Mounting of standard and servo gear units possible
- Direct mounting of gear unit possible
- Resolver or high-resolution absolute encoder possible
- Adjustable plug connector
- Optional forced cooling fan
- Optional 24 V brake
- KTY sensor for thermal motor protection

2.3.2 Design of the CM/DS motor

CM/DS servomotors feature a wide torque range, good control characteristics with high external masses, the use of powerful working brakes, and a wide range of options.

CM/DS servomotors are motors with housing.

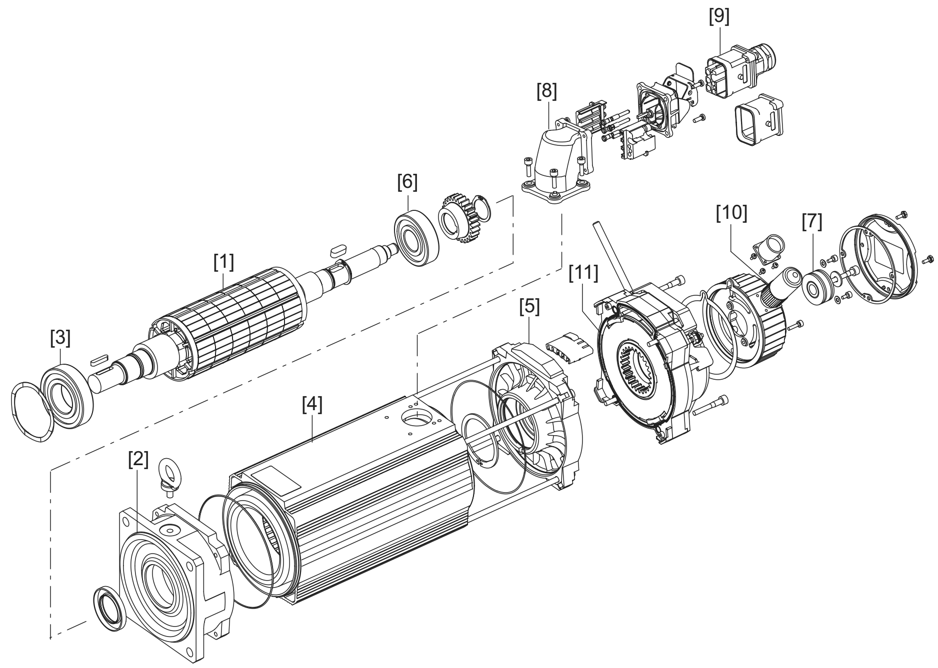

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Fig. 5: Design of the SEW-EURODRIVE CM synchronous servomotor

[1]	Rotor	[7]	Resolver
[2]	Flanged end shield	[8]	Connector housing
[3]	Grooved ball bearing	[9]	Power plug, cpl.
[4]	Housing with stator	[10]	Signal plug, cpl.
[5]	Non drive-end bearing shield	[11]	Brake, cpl.
[6]	Grooved ball bearing		

Features and options of the CM/DS motor

- Up to 4 x overload capacity
- Stator with pull-in winding
- Mounting of standard and servo gear units possible
- Direct mounting of gear unit possible
- Resolver or high-resolution absolute encoder possible
- Connectors or terminal boxes
- Optional forced cooling fan
- Optional brake with working capacity
- TF or KTY sensor for thermal motor protection
- Optional second shaft end
- Optional reinforced bearings

2.3.3 Design of the CMD motor

CMD servomotors are very compact and feature optimized speed adjustment for direct drive technology and a svelte variant concept.

CMD servomotors are motors without housing.

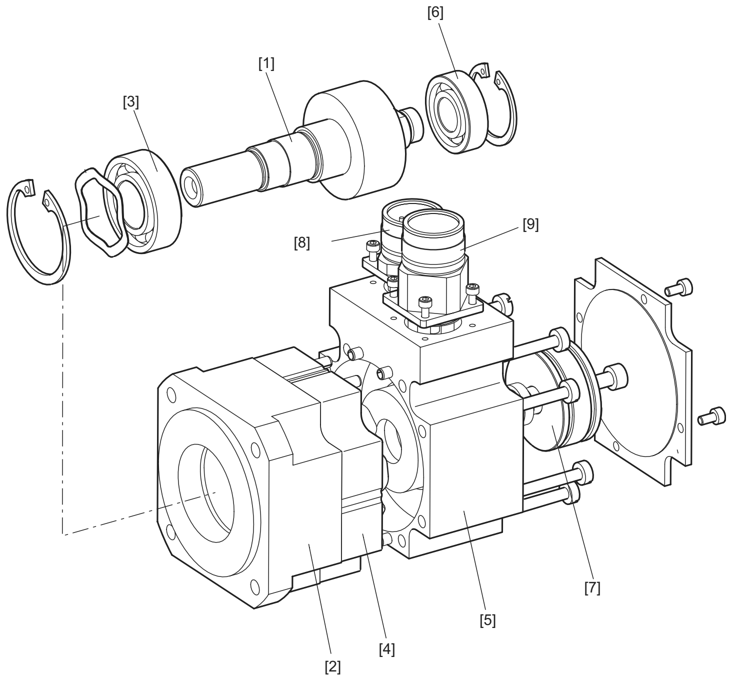

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Fig. 6: Design of the SEW-EURODRIVE CMD synchronous servomotor

[1]	Rotor	[6]	Grooved ball bearing
[2]	Flanged end shield	[7]	Resolver
[3]	Grooved ball bearing	[8]	Signal plug connector
[4]	Stator	[9]	Power plug connector
[5]	Non drive-end bearing shield		

Features and options of the CMD motor

- Up to 6 x overload capacity
- Stator with single-tooth winding
- Optional 24 V brake
- Resolver or high-resolution absolute encoder possible
- KTY sensor for thermal motor protection

2.3.4 Design of the rotor

The rotor of synchronous servomotors is equipped with permanent magnets.

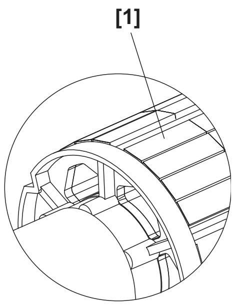

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Fig. 7: Magnets attached to the rotor

[1] Attached magnets

These magnets are generally composed of the sintered rare-earth material neodymium-iron-boron. The magnetic properties of this material greatly exceed those of common ferrite magnets, allowing for a compact construction with optimal power yield.

2.4 Theory of operation of synchronous servomotors

Connecting the motor to a suitable servo inverter generates the stator rotating field in the windings. This rotating field exerts a magnetic force on the rotor. The magnetic coupling between the stator and the rotor accelerates the rotor and which turns with the same angular velocity as the rotating field. In other words, it turns synchronously.

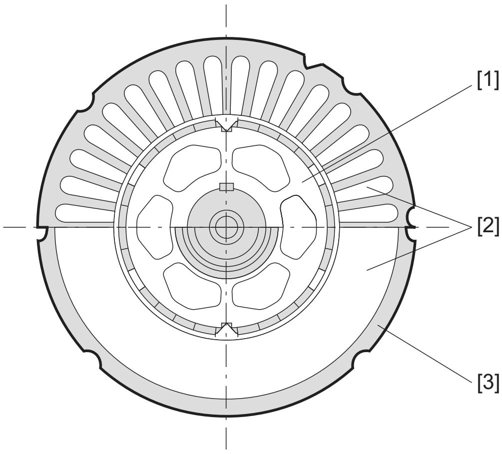

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Fig. 8: Schematic representation of a pull-in winding

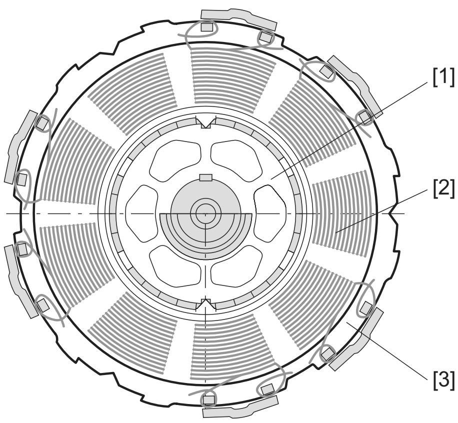

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Fig. 9: Schematic representation of a single-tooth winding

[1]	Rotor	[3]	Laminated core
[2]	Winding		

A strain put on the motor results in a lag of the rotor rotating field in relation to the stator rotating field. The poles of the rotor lag behind those of the stator rotating field by the rotor displacement angle α. The torque increases the more the greater rotor displacement angle is. The maximum torque is reached with a rotor displacement angle of α = 90°, when the poles of the rotor are exactly between the two poles of the stator.

The stator pole that is leading the rotor poll "pulls" the rotor and the lagging stator poll "pushes" the rotor.

Rotor displacement angles α greater than 90° reduce the torque. The motor is in an unstable operating position and might remain still, causing thermal damage.

The following applies: M = f (V, I, sin α).

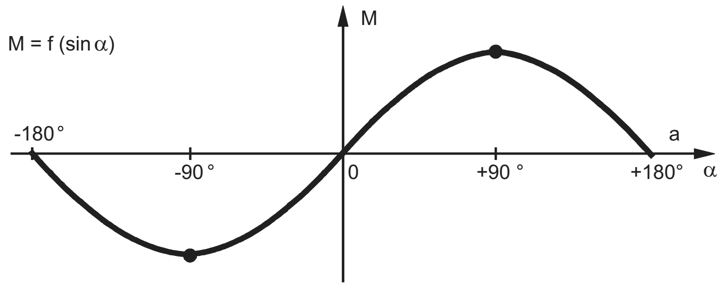

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Fig. 10: Rotor displacement angle and torque dependency

2.4.1 Optimal operating point

To operate the synchronous motor with maximum torque, a rotor displacement angle of α = 90° of is required. Accordingly, the stator pole must always lead by 90° in motor operation and lag by 90° in regenerative operation. The motor control ensures that the three phase currents of the motor are calculated from a specified torque and the current setpoint according to the motor model, in order to generate the necessary resulting magnetic field.

To do so, the position of the rotor must be recorded using a suitable encoder. Depending on the direction of torque, 90° are added to the rotor actual position or subtracted from it. The corresponding phase currents are then calculated.

The corresponding position of the stator rotating field is determined for each position of the rotor. The rotor defines the size and assignment of the stator field; in other words, the rotor turns the stator field.

The rotor displacement angle α in this context is an electrical angle. For a 6-pole motor, 90 degrees correspond to 30 mechanical degrees.

2.4.2 Current ratios in the stator

The current ratios in the stator are as follows:

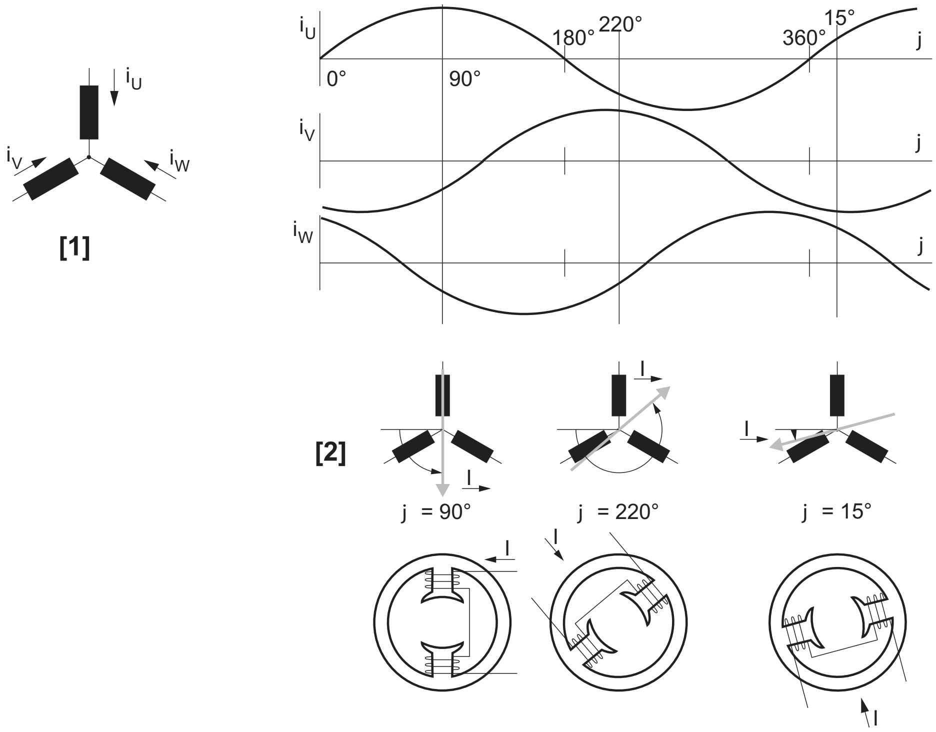

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Fig. 11: Current ratio in the stator

[1] Current space vector I = vectorial sum of the currents i_U, i_V, i_W

[2] The figure depicts the ratios in the stator with regard to the generation of torque at various points in time

2.4.3 Sinusoidal supply

The majority of synchronous servomotors offered today are powered by sinusoidal current, which is injected into the stator winding by a suitable servo inverter. The three motor phases are energized at the same time.

Figure 12 depicts the amounts of current and voltages at time t_n.

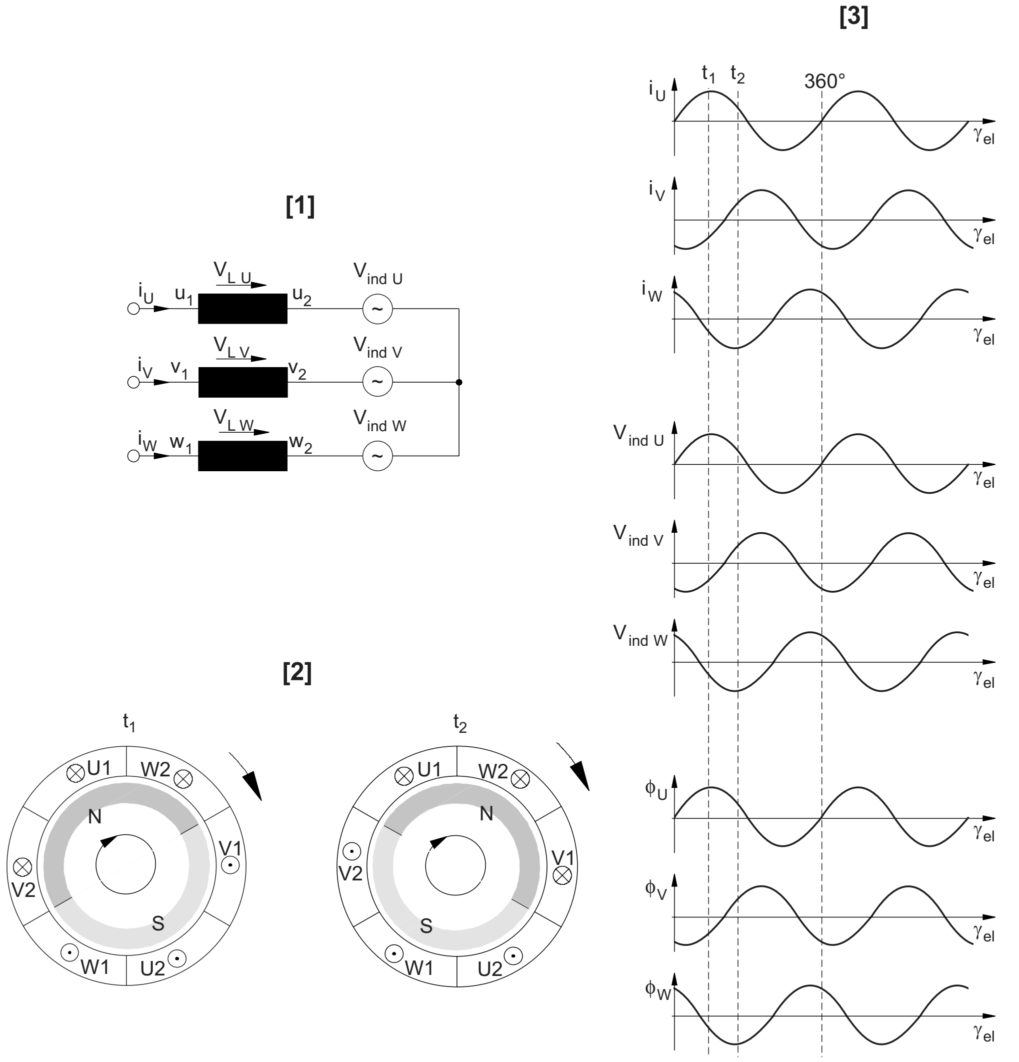

Fig. 12: Sinusoidal supply

[1]	Equivalent circuit diagram of a synchronous servomotor
[2]	Position of the rotor at time t_n
[3]	Diagram: Current, voltage, and flux over time with constant voltage
V_{ind}	Inducted voltage due to rotation of rotor (EMF)
V_L	Inductance voltage drop

The servo inverter releases a clocked DC voltage from the link circuit in every phase. The effective value of the output terminal voltage is the same as a genuine sinusoidal voltage. This clocked DC voltage (sine-evaluated modulation) injects a sinusoidal current into the motor that then stimulates a sinusoidal magnetic flux. This causes a high torque and speed stability, even for low speeds.

Usually, synchronous servomotors are equipped with resolvers with sin/cos absolute encoders. With the data determined by the position encoders, the servo inverter ensures that the rotor displacement angle is 90°. However, the position encoders must be exactly aligned with the poles of the permanent magnets. Only then can the external magnetic field of the stator form with a 90° offset. This is also called commutation.

2.4.4 Block-shaped supply

In addition to the sinusoidal supply of motors, there is also the block-shaped supply that is only of secondary importance nowadays. As the name says, the DC link circuit supplies the motor with block-shaped voltages.

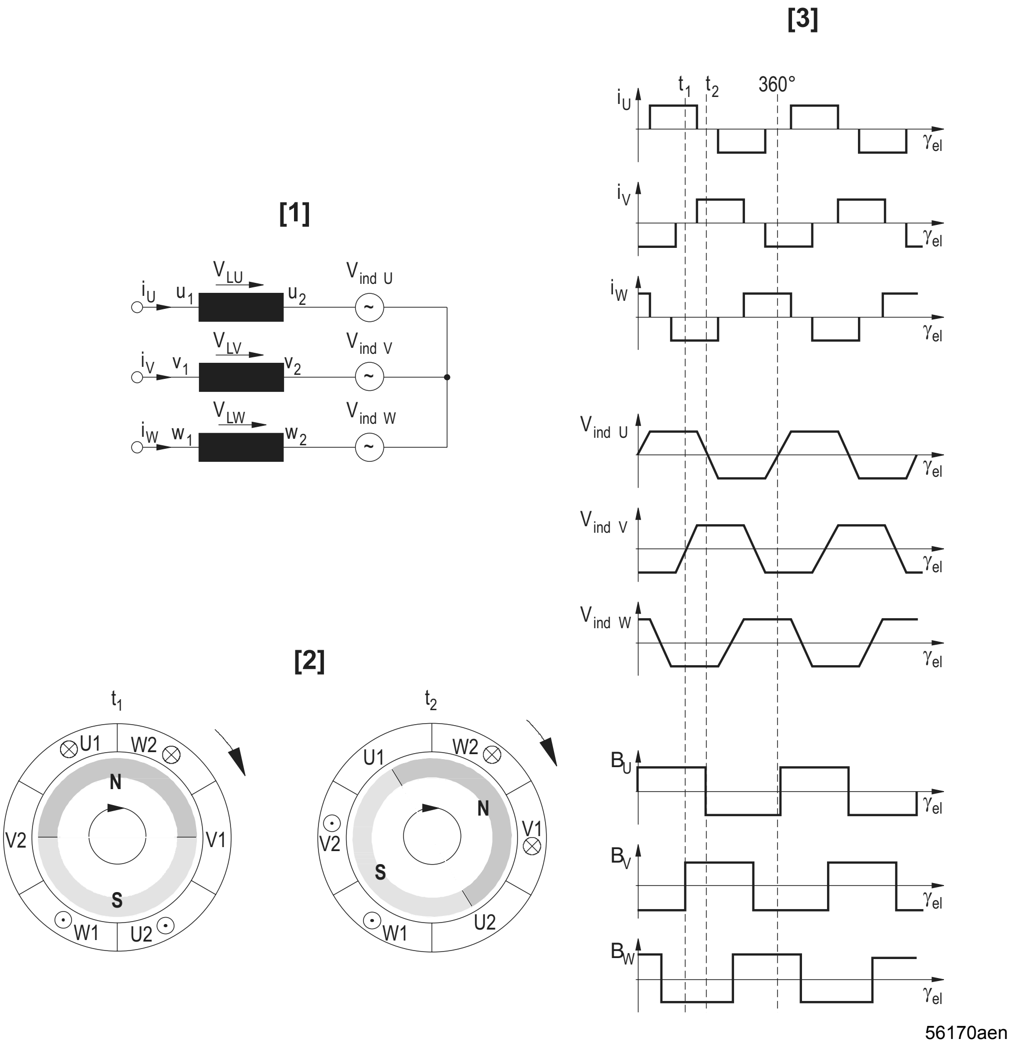

Fig. 13: Block-shaped supply

[1] Equivalent circuit diagram of a synchronous servomotor
[2] Position of the rotor at time t_n
[3] Diagram: Current, voltage, and flux over time with constant voltage
V_{ind} Inducted voltage due to rotation of rotor (EMF)
V_L Inductance voltage drop

Block-shaped currents are injected into the motor windings, inducing trapezoidal voltages in the motor. Due to the design, the air gap is distributed rectangularly, resulting in constant torque generation.

A rotor position encoder controls the current controller during the block-shaped supply.

An additional encoder (generally a tacho-encoder) is required for speed detection.

The absolute position of the rotor is determined using a position encoder.

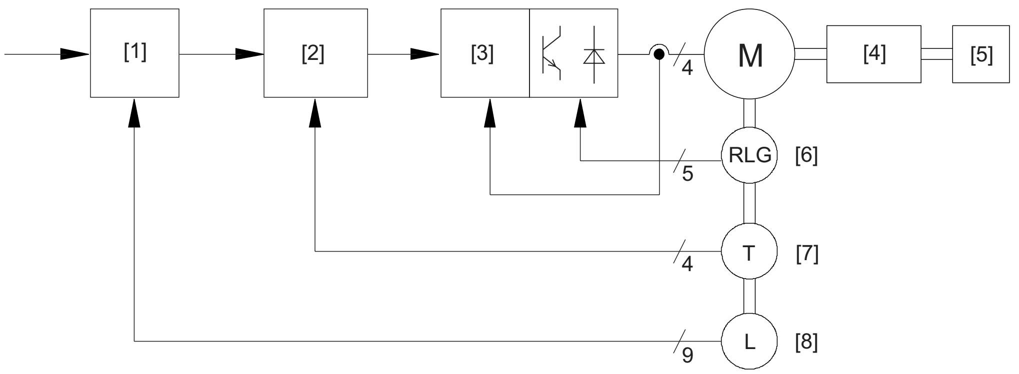

Fig. 14: Control structure with encoder systems for a motor with a block-shaped supply

[1]	Position	[5]	Load
[2]	Speed	[6]	Rotor position encoder
[3]	Current	[7]	Tacho-generator
[4]	Gear unit	[8]	Position encoder

Advantages and disadvantages of block-shaped supply in comparison with sinusoidal supply:

Advantages of block-shaped supply

- Simple (and therefore cheaper) encoder systems such as hall probe, light barrier for determining the rotor position
- Simple generation of the control signal for the current

Disadvantages of block-shaped supply

- Worse speed stability
- Worse torque stability, especially for low speeds
- Additional encoder for speed required

2.4.5 Thermal and dynamic limit characteristic curve

Dynamic limit characteristic curve

The dynamic limit characteristic curve provides information about which maximum torque the motor can provide at which speed.

Note that the servo inverter must supply sufficient current for the motor to reach its maximum torque.

During project planning, also observe that the maximum torque drops in the upper speed range. This is due to the countervoltage generated in the motor by the law of induction. The rotor's permanent magnets generate this voltage in the stator coils. This countervoltage causes the servo inverter to no longer be able to inject the current required for the maximum torque as the voltage distance between the servo inverter output voltage and the induced countervoltage becomes too low.

Figure 15 shows the dynamic limit characteristic curve of a CM90M synchronous servomotor for speed classes 2000, 3000, 4500 and 6000.

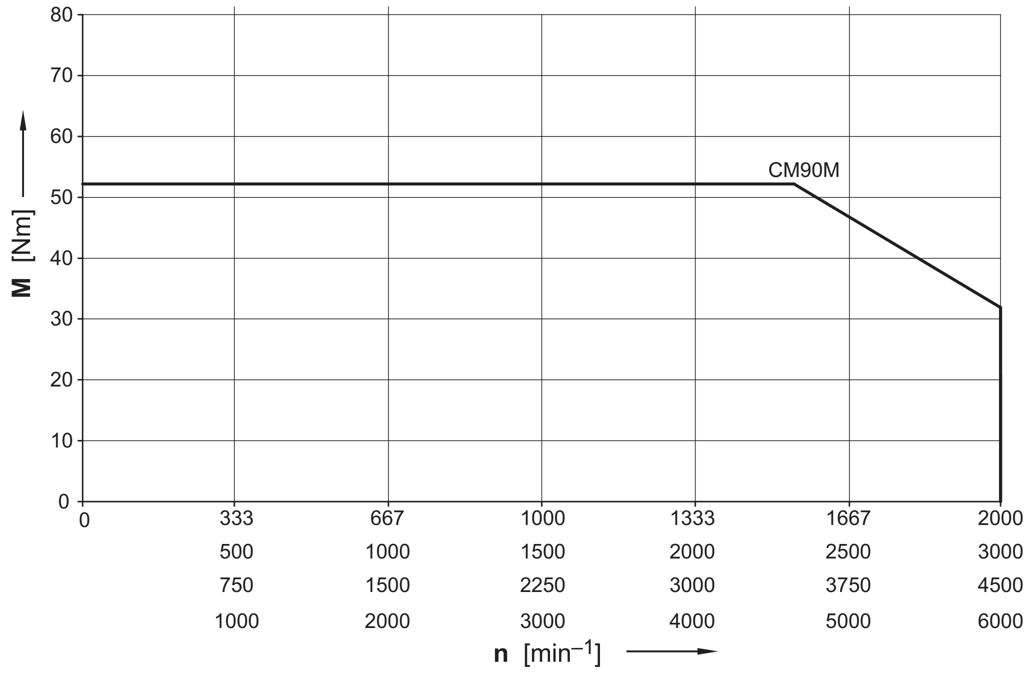

Fig. 15: CM90M dynamic limit characteristic curves

For project planning, note that the maximum torque with the associated speed can lie below or, at the maximum, on the dynamic limit characteristic curve of the motor. For more information, see section 8, "Project Planning".

Thermal limit characteristic curve

The mean motor speed and the effective torque are calculated during project planning to determine the thermal loading of the motor. This information is used to determine the operating point of the motor.

This operating point must lie below the thermal limit characteristic curve of the motor; otherwise the motor will be thermally overloaded. Note that the characteristic curve declines with constant speed. For this reason, it is necessary to determine the operating point during project planning. The square of the mean moment M_{eff} and the mean speed $\bar{n}$ form the operating point.

The decline of the characteristic curve is mostly due to eddy-current, hysteresis, and iron losses.

Figure 16 displays the thermal limit characteristic curve of a CM90M synchronous servomotor for speed class 6000.

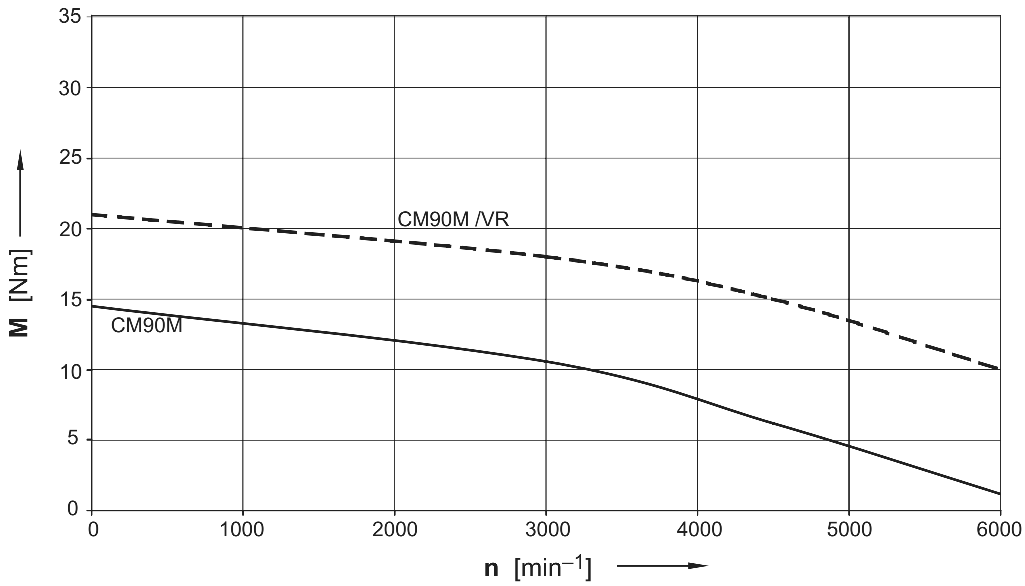

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Fig. 16: CM90M thermal limit characteristic curves

The "/VR" behind the motor designation means that the motor is equipped with a forced cooling fan.

2.5 Design of asynchronous servomotors

Basic design The basic design of an asynchronous servomotor consists of:

- A rotor with shorted winding
- A stator with suitable winding
- Power connection (terminal box)
- An encoder

In the following, you will find descriptions of asynchronous servomotors using the motor series CT/CV from SEW-EURODRIVE.

2.5.1 Design of the CT/CV motor

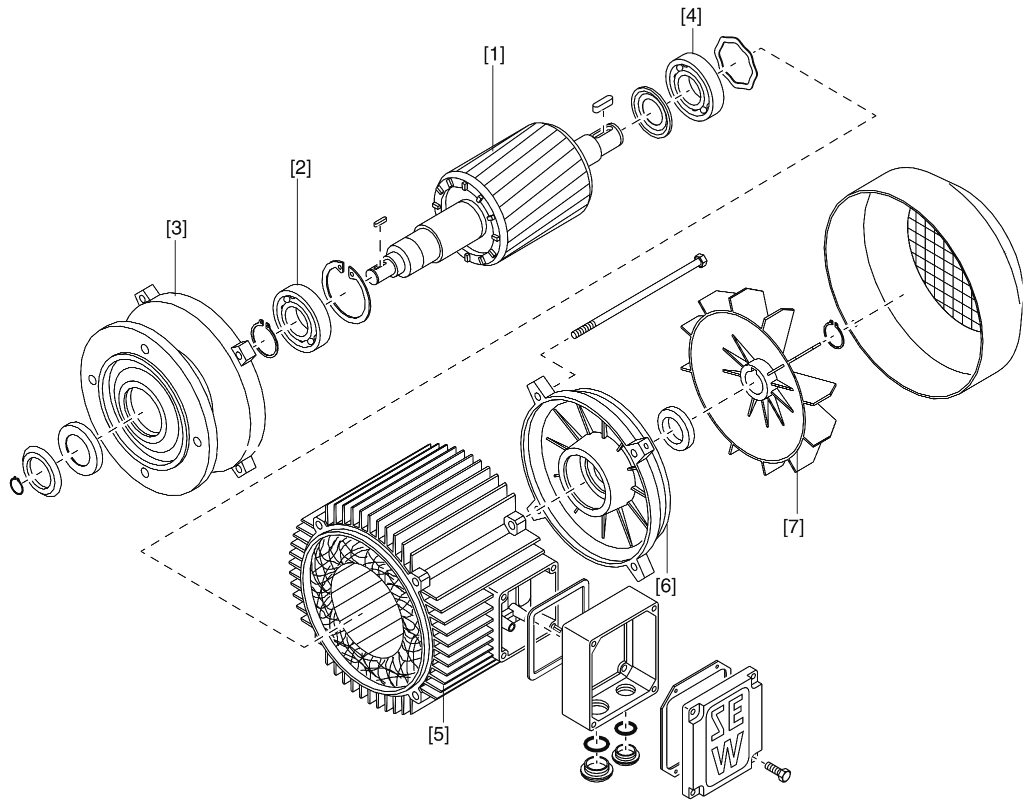

Fig. 17: Design of the SEW-EURODRIVE CT/CV asynchronous servomotor

[1]	Rotor, cpl.	[5]	Stator, cpl.
[2]	Grooved ball bearing	[6]	Non drive-end bearing shield
[3]	Flanged end shield	[7]	Fan
[4]	Grooved ball bearing		

The stators of asynchronous and synchronous servomotors motors are basically designed the same, whereas the rotors are fundamentally different. Asynchronous servomotors have squirrel cage rotors in which magnetic fields are generated by induction.

The stator basically consists of three coils wound around a ferromagnetic core lamination at an offset of 120°. The coil ending points can be connected in a star or delta connection.

Features and options of CT/CV motors

- Torque range from 3 to 200 Nm
- Stator with pull-in winding
- 3 x overload capacity
- Good control characteristics for large external masses
- Forced cooling fan required for continuous low speeds
- Encoder system required to determine rotor position
- Brake possible

2.6 Theory of operation of asynchronous servomotors

The rotor of an asynchronous servomotor is designed as a cylindrical cage. The individual bars of the cage are held together by short-circuit rings. During operation, current flows into the bars through the short-circuit rings. Each current-carrying conductor forms a magnetic field. If the magnetic field is offset from the magnetic field of the stator, the rotor experiences force. This force is at its maximum when the magnetic field of the rotor is perpendicular to the magnetic field of the stator.

Using a field-oriented control mode, both magnetic fields can be calculated such that the asynchronous servomotor can be operated considerably more dynamically than otherwise possible.

Field orientation means that two existing magnetic fields are oriented against each other. The field orientation is the same for synchronous and asynchronous servomotors. Due to the design of the rotor, a large number of physical parameters must be taken into account for asynchronous servomotors to produce constant magnetization of the rotor. As asynchronous servomotors do not have permanent magnets, the magnetic flux in the rotor must be formed using the magnetic field of the stator. Thus, the stator current is responsible for the formation of the flux and the torque.

With transformers, the primary winding is connected to the secondary windows through the laminated core where a voltage is induced. Similarly, the stator winding is coupled with the squirrel-cage rotor through the air gap. According to the rule of induction:

$$V_i = -N \times \frac{\Delta\Phi}{\Delta t}$$

V_i	Induced voltage [V]
N	Number of windings
$\Delta\,\Phi\,/\Delta t$	Change in time of the magnetic flux [Wb/s]

From the equation, it is apparent that a change in flux is required to maintain the voltage of the secondary windings and therefore their current as well. This rule is similar to transformers with which DC voltage cannot be transferred.

The current supply of the stator results in a magnetic flux that flows through the rotor. Lenz's law states that all induced voltages resulting from a change in the magnetic flux act in such a direction that the currents they generate oppose the cause of the induction. Therefore, the current generated in the rotor opposes the change in flux. Due to the ohmic losses in the rotor, its current decays, as long as there is no change in flux from the stator current. The decay process takes place with the electric time constant T of the rotor:

$$T_r = \frac{L_r}{R_r}$$

T_r	Rotor electric time constant
L_r	Rotor inductance
R_r	Rotor resistance

Modern current-controlled control modes, such as the CFC mode (**C**urrent **F**lux **C**ontrol) developed by SEW-EURODRIVE, can generate a magnetic field with a known direction and strength and inject a perpendicular rotor current. This control mode makes it possible to run asynchronous motors with servo characteristics.

Example

Below, the basic theory of operation of a current-controlled field control is explained using an asynchronous motor (ASM):

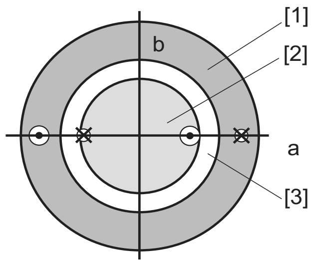

Fig. 18: Stator current at t_0

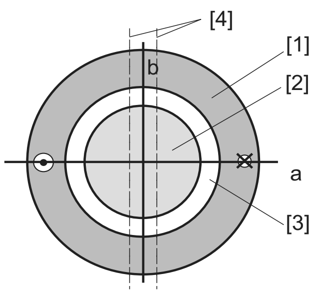

Fig. 19: ASM magnetization

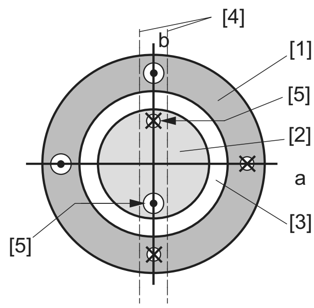

Fig. 20: Torque generation

[1]	Stator
[2]	Rotor
[3]	Air gap
[4]	Field lines
[5]	Live conductor with display of current flow direction

1. The stator is energized at t_0, see figure 18. At first, the direction of the initial current flow is random. The magnetic field of the induced current opposes the change of the magnetic flux (Lenz's law). In other words, the currents of the rotor and stator oppose each other.
2. The asynchronous servomotor is magnetized as the condition at t_0 is maintained until current in the rotor has decayed. The current decays due to the ohmic resistance in the rotor. The time required for the magnetization is defined by the rotor's electric time constant T_r. The decayed condition can be considered met with 5 × T_r. The asynchronous servomotor can now be considered magnetized; see figure 19.

3. The **abrupt** injection of an additional current component that is **perpendicular** to the initial current flow causes a current itself; see figure 20. This condition is comparable to the condition described under point 1, however:
   - The current flow of the stator conforms to the current in point 1
   - The wait here is substantially shorter than with point 1

The current injected into the stator, I_{sd}, determines the magnetization. The rotor current, I_q, is responsible for the formation of torque and corresponds to the current component I_{sq} turned by 180°. As both current components are known for the field orientation, the torque can be determined. According to the laws of magnetism, the current-carrying conductor, the rotor in this case, experiences and is acted upon by a force F in the magnetic field. This force determines the torque.

The specific rectangular configuration causes the rotor current responsible for forming torque to be used optimally. The resulting magnetic field begins to align itself with the angle of the stator current. The velocity of the alignment follows an e function and is determined by the rotor's time constant, T_r.

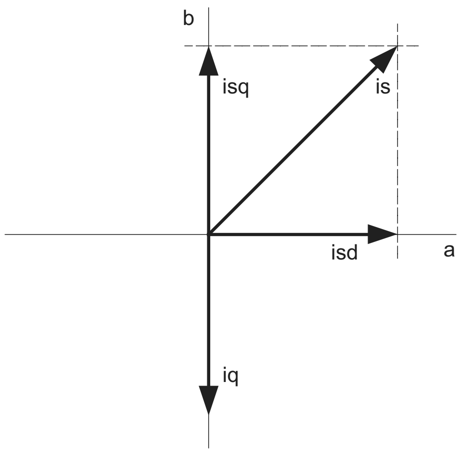

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Fig. 21: Simplified representation of the currents in the stator and rotor at time t_1

isq	First stator current component (torque generating, at t_1)
is	Stator current at t_1
isd	First stator current component (magnetizing, at t_1)
iq	Rotor current at t_1

If the stator's current flow is held in this way for a time of 4 × T_r ... 5 × T_r, the rotor current falls to zero and the magnetic field aligns itself with the angle of the stator current. In this case, the resulting torque would be zero and the field orientation would be lost.

Therefore, the wait time t is chosen to be very small in relation to the rotor constant T_r.

$$t << T_r$$

In this case, the stator currents are realigned when the stator is supplied with current.

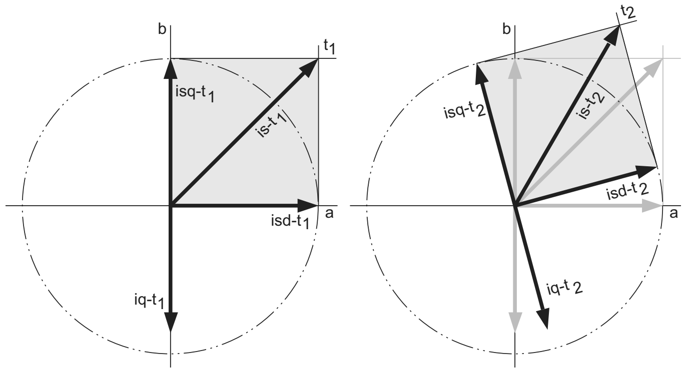

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Fig. 22: Simplified representation of the change in current in the stator and rotor at time t_2

isd-t_1	First stator current component (magnetizing, at t_1)
is-t_1	Stator current at t_1
isq-t_1	Second stator current component (torque generating, at t_1)
iq-t_1	Declining rotor current at t_1
isd-t_2	Realigned first stator current component at t_2
is-t_2	Stator current after realignment at t_2
isq-t_2	Realigned second stator current component at t_2
iq-t_2	Rotor current after realignment at t_2

Today's servo controllers have sampling intervals between 62.5 and 250 µs, depending on the target application for which they were designed. After the sampling interval, the stator current is realigned, and consequently, the rotor current is as well. Due to the short sampling interval, the angle from one time period to the next is very small. The small change in angle causes a small change in the magnetic flux, and therefore in the torque.

The field orientation is created by replacing the stator current components with the realigned stator currents $\mathbf{I}_{sd}$ and $\mathbf{I}_{sq}$. Consequently, the vectors of the stator describe a circular path:

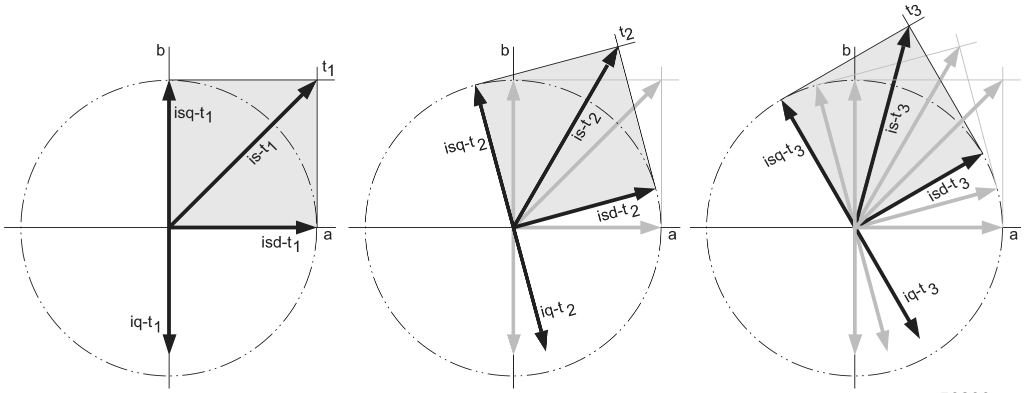

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Fig. 23: Simplified representation of the change in current in the stator and rotor at time t_n

isd-t_1	First stator current component at t_1
is-t_1	Stator current at t_1
isq-t_1	Second stator current component at t_1
iq-t_1	Rotor current at t_1
isd-t_2	Realigned first stator current component at t_2
is-t_2	Stator current after realignment at t_2
isq-t_2	Realigned second stator current component at t_2
iq-t_2	Rotor current after realignment at t_2
isd-t_3	Realigned first stator current component at t_3
is-t_3	Stator current after realignment at t_3
isq-t_3	Realigned second stator current component at t_3
iq-t_3	Rotor current after realignment at t_3

2.6.1 Motor characteristic curve

Using the asynchronous servomotor CV100M4 from SEW-EURODRIVE, important data for project planning including the motor characteristic curve will be looked at in more detail below. Usually, the following motor data is known:

Motor type	: CV100M4
Rated speed N_{rated}	: 2100 1/min
Rated torque M_{rated}	: 15 Nm
Rated current I_{rated}	: 8.1 A
Transition speed n_{trans}	: 1760 1/min (together with a 4-kW servo inverter)

Special attention should be paid to the transition speed during project planning. The transition speed is the speed up to which the maximum torque is available for the utilizing the maximum servo inverter peak current. If the motor is operated above the transition speed, the available torque is greatly reduced. This can be clearly seen in the following figure.

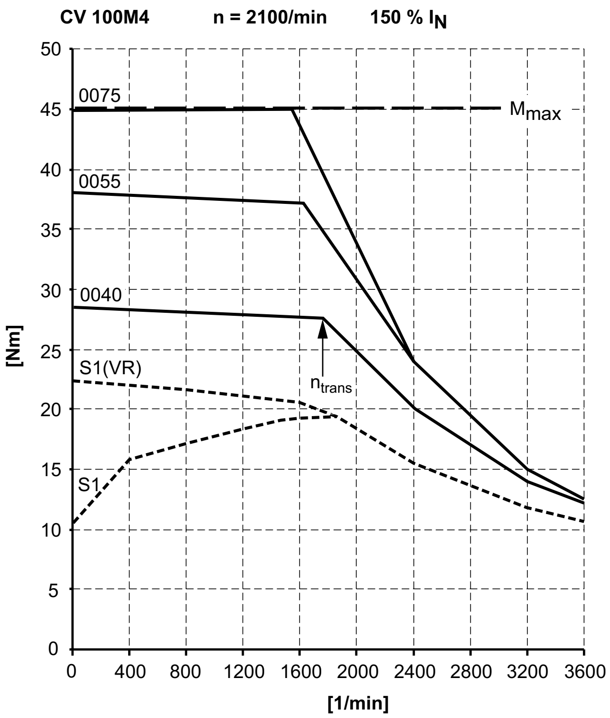

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Fig. 24: Characteristic curves of asynchronous servomotor CV100M4

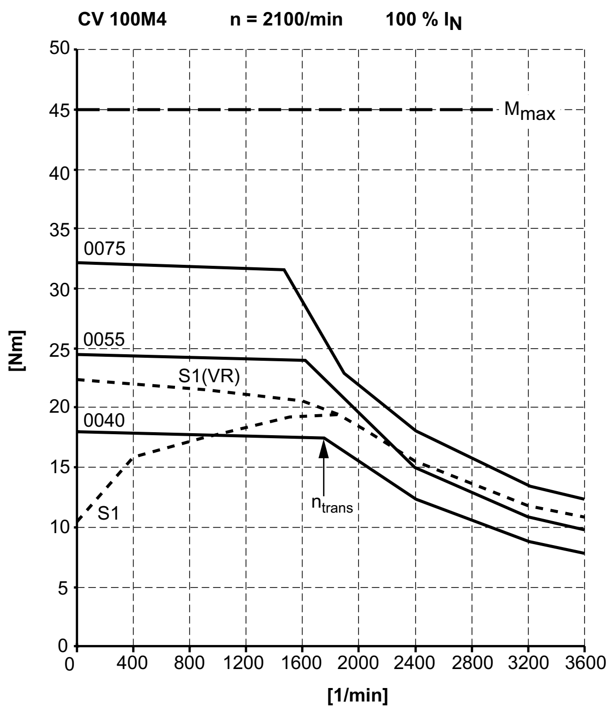

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Fig. 25: Characteristic curves of asynchronous servomotor CV100M4

M_{max}	:	Maximum torque of the motor
0075	:	Torque characteristic curve with 7.5-kW servo inverter at 150 % / 100 % of the rated current of the servo inverter
0055	:	Torque characteristic curve with 5.5-kW servo inverter at 150 % / 100 % of the rated current of the servo inverter
0040	:	Torque characteristic curve with 4-kW servo inverter at 150 % / 100 % of the rated current of the servo inverter
S1 (VR)	:	S1 characteristic curve (continuous duty) with forced cooling fan
S1	:	S1 characteristic curve (continuous duty)
n_{trans}	:	Transition speed, using a 4-kW servo inverter

The servo inverter power is selected according to the required torque. The permitted combination of a motor and servo inverter with different powers results in different torque characteristic curves.

During project planning, do not forget that the effective motor torque can lie below or maximally on the S1 characteristic curve at medium speed. If the effective motor torque lies above the S1 characteristic curve at medium speed, the motor is thermally overloaded.

The torque characteristic curves with information on the servo inverter power provide information on which torques are available for which speeds. However, they do not indicate whether these torques can be continuously delivered. For this purpose, the S1 characteristic curve is essential.

If you use a motor with a low speed might require you to equip the motor with forced cooling fan to avoid thermal overload. The S1 (VR) characteristic curve makes it clear that the motor can continuously provide a considerably higher torque especially in the lower speed range. During project planning of the drive, it is possible to determine the operating point using the effective motor torque and the mean speed. With the operating point, it is possible to determine whether a forced cooling fan is required or not.

The overload capacity of the permitted motor/servo inverter combinations result in different dynamic torque characteristic curves. Again, for project planning, note that the torques are not continuously available due to the danger of thermal overload. For more information, see section 8, "Project Planning".

2.7 Synchronous linear motors

The theory of operation for synchronous linear motors is basically the same as for rotary synchronous servomotors. Linear motors are used when the highest requirements are placed on dynamic properties and positioning accuracy, for example. Because a synchronous linear motor consists of a large number of components, it is not assembled until it is installed into a machine.

The following illustration is a schematic representation of the design of a complete linear drive system.

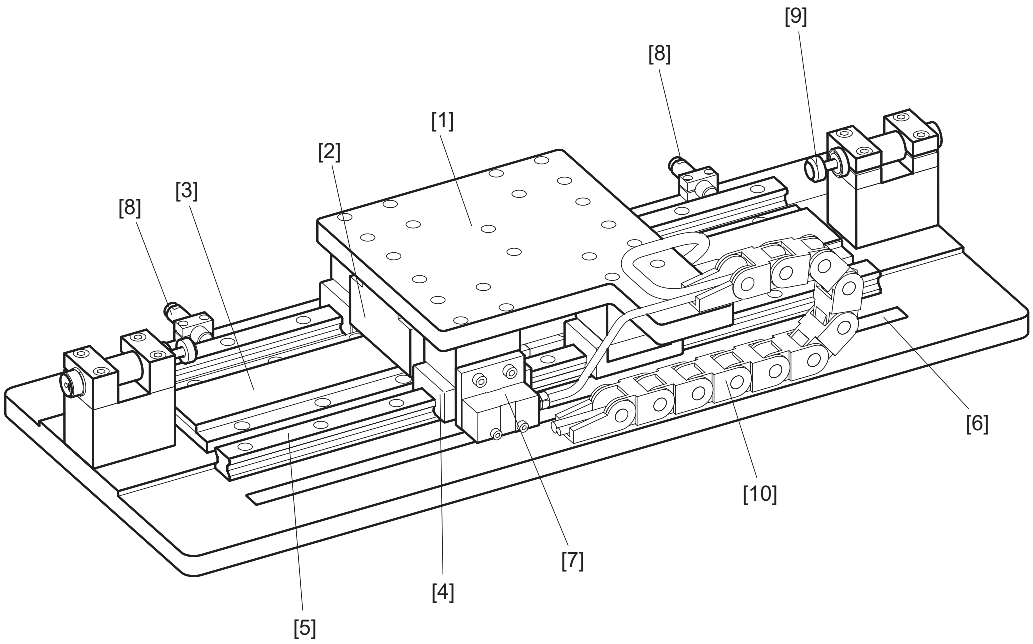

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Fig. 26: Linear drive system

[1]	Primary carrier	[6]	Ruler
[2]	Primary	[7]	Measuring head
[3]	Secondary	[8]	Limit switches
[4]	Guide carriage	[9]	Buffer
[5]	Guide rail	[10]	Power supply

Advantages of synchronous linear motors

The advantages of a synchronous linear motor compared to a rotary system:

- Higher speeds
- Higher accelerations
- Direct drive (no gear unit, toothed belt, etc. required); in other words, clearance
- Practically wear-free
- Higher positioning accuracy

Application

Synchronous linear motors are mostly used in the following industries:

- Handling systems (transport and logistic applications)
- Packaging technology
- Machine tool construction
- Assembly technology
- Special machine design

In these industries, synchronous linear motors replace traditional non-direct-drive solutions such as spindle, rack and pinion, belt, and chain drives.

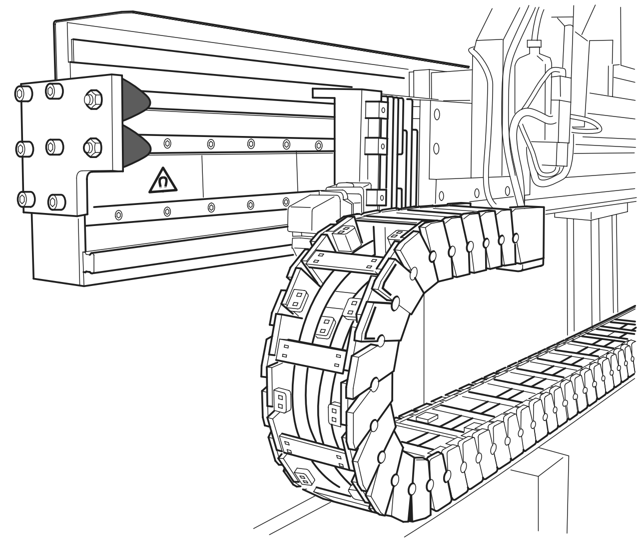

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Fig. 27: Synchronous linear motor in a handling system

2.7.1 Principles of the synchronous linear motors

There are two synchronous linear motor principles:

- The long-stator principle
- The short-stator principle

Long-stator principle

With this principle, the travel distance is stipulated by one or more primaries that are longer than the magnetic strip. The magnetic strip is located on the moved travel carriage (secondary). In other words, the secondary does not require a power supply and makes a theoretically unlimited travel distance possible.

The long-stator principle is generally encountered in transport and logistic applications.

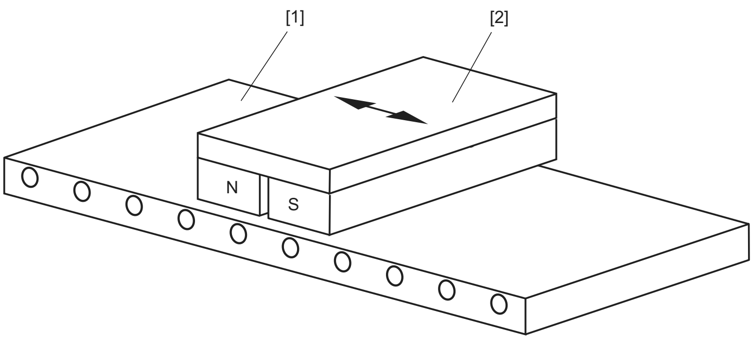

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Fig. 28: Long-stator principle

[1] Primary: Stator with windings

[2] Secondary: Permanent-field reaction rail

Short-stator principle

With this principle, the primary is moved which is short in comparison with the magnetic strip. The short-stator principle is generally encountered in servo applications in mechanical engineering.

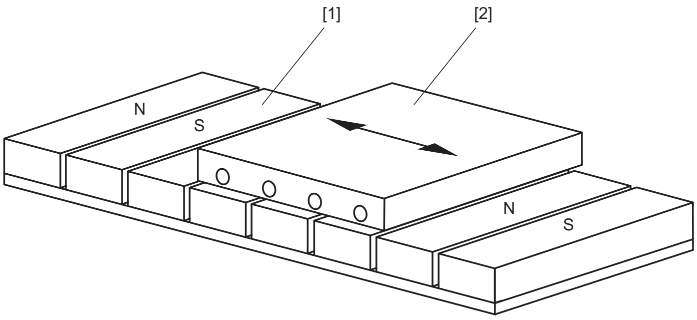

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Fig. 29: Short-stator principle

[1] Secondary: Permanent-field reaction rail
[2] Primary: Stator with windings

Because of the widespread usage, only the short-stator principle will be discussed further in this volume.

Design and working principle of the short-stator principle

A synchronous linear drive, similar to a rotary drive, consists of two parts: a primary and a secondary.

Relating to the theory of operation:

- The primary of the linear motor corresponds to the stator of the rotary motor. The primary includes the laminated core, the motor winding, and the temperature sensor.
- The secondary of the linear motor corresponds to the rotor of the rotary motor. The secondary consists of a carrier material made of steel with the attached permanent magnets.

The primary and secondary are encapsulated.

It is clear that the theory of operation of the linear and rotary motors is principally the same when the rotary motor cut open and "bent straight"; see figure 30.

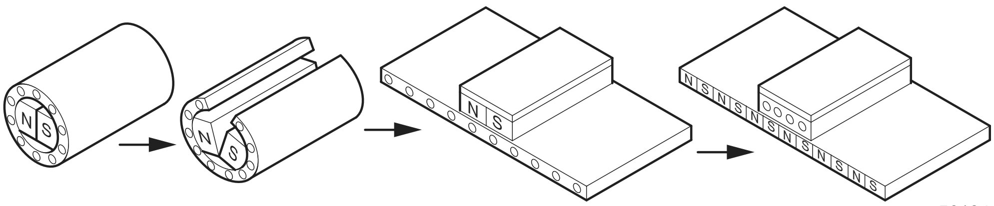

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Fig. 30: Principle of the linear motor

Unlike with rotary motors, either the primary or secondary can be moved for linear motors.

To achieve the performance data, it is very important that an exact air gap is maintained between the primary and secondary for linear servomotors. An increase in the air gap will result in a reduction of the motor power. An air gap that is too large will cause the motor to stand still Consequently, exact preparation of the mounting surface is the basic prerequisite for smooth system operation. The air gap is set via the linear guide system and the mounting plate.

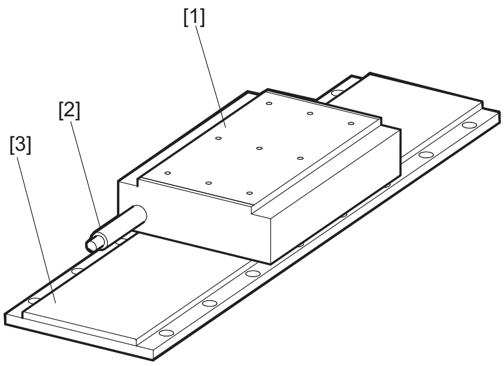

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Fig. 31: Design

[1]	Primary
[2]	Electrical connection
[3]	Secondary with permanent magnets

2.7.2 Motor characteristic curve

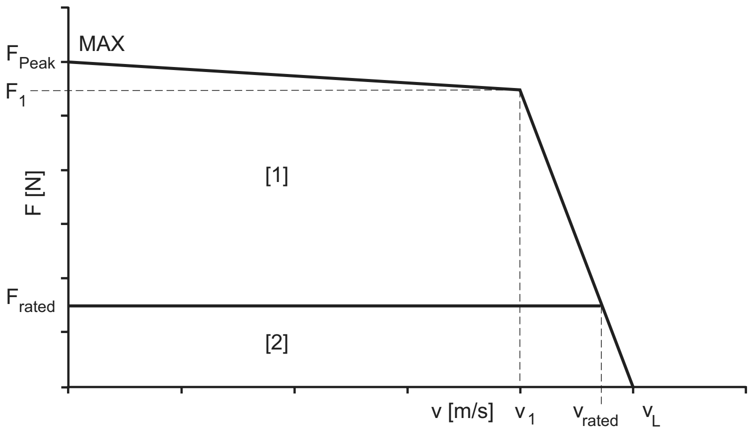

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Fig. 32: Motor characteristic curve

[1]	Dynamic limit forces
[2]	Thermal limit forces
F_{rated}	Permanent force [N]
	Permanent force depends on: - The size of the primary flange surface - The strength of the primary flange surface - The ambient temperature - The altitude
F_1	Maximum force [N] that is available up to velocity V_1
F_{Peak}	Maximum force [N]
V_L	Theoretical maximum traveling velocity [m/s]
V_1	Velocity [m/s] up to which force F_1 is available
V_{rated}	Velocity [m/s] up to which the rated force is available

The limit characteristic curve provides information about which peak forces F_{Peak} and F_{rated} the motor can apply at the relevant velocities. Note that a suitable heat transfer from the motor core to the environment must be present for thermally loading the motor to ensure sufficient cooling. The flange surface and the thickness of the primary are decisive factors in determining the size of the cooling surface.

There are two general types of cooling:

- Convection cooling
- Water cooling

Depending on the application, other measures might be required:

- Forced cooling fan with convection cooling
- Water cooling
- Water cooling with additional thermal encapsulation

Convection cooling

The cooling basically works by dissipating the heat and warming the ambient air. The heat transfer must be ensured by planning the surface of the motor accordingly.

Additional fans installed in the motor ensure a constant airflow and help remove the heat energy.

Properties of a cooling system with forced cooling fans:

- High cooling capacity
- Simple principle making for lower technical and financial costs

SEW solution: SL2-Advance System and SL2-Power System

SEW-EURODRIVE offers a fully integrated assembly and cooling system with the SL2-Advance System and SL2-Power System synchronous linear motors which replace extensive and expensive water cooling with a really simple type of air cooling. This air cooling that works according to the principle of convection is a an inexpensive variant with almost the same power yield.

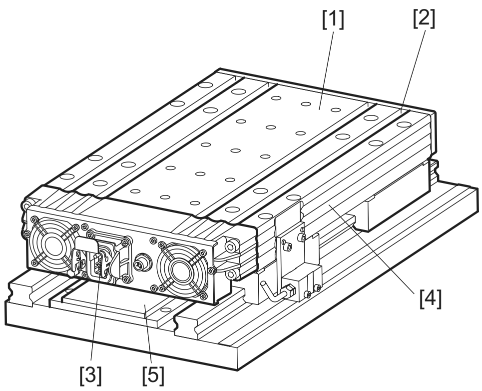

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Fig. 33: SL2-Advance System and SL2-Power System synchronous linear motor

[1]	SL2-Advance/SL2-Power System	[4]	Primary (not visible) integrated with motor cooling unit
[2]	Prepared grooves as retaining system for customer setup	[5]	Secondary
[3]	Electrical plug connector		

This principle allows for a considerably higher utilization of the rated motor force.

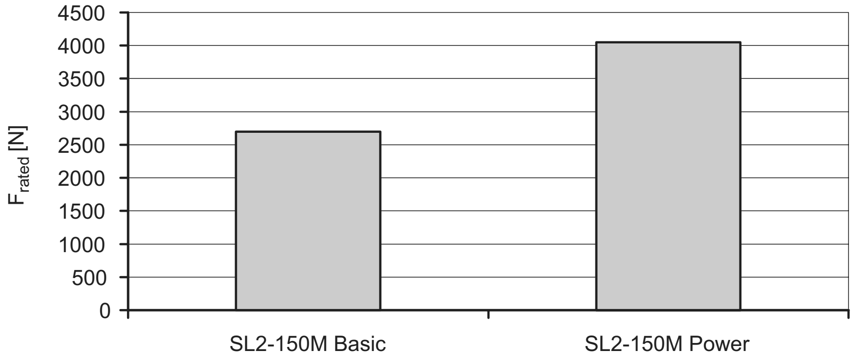

Fig. 34: Rated force for SL2-150M in Basic and Power versions

In addition to their thermal advantages, the motor system of the SL2-Advance and SL2-Power motors are very easy to install and mount in the machine. Additionally, this design simplifies the load mounting and maintenance to be performed by the customer.

Without SL2-Advance and SL2-Power motors, the user must acquire a certain know-how to assemble the linear motor system. The rated force of the system can only be reached if a sufficient and stable design was selected that can withstand the high accelerations. Take the heat dissipation and the effects of thermal expansion into account.

Water cooling

Water cooling is a common way of cooling linear motors in mechanical engineering.

The cooling channels are attached in the primary of the linear motor and are connected to a water circuit.

Features of this system:

- High cooling capacity
- Due to the design of the motor, it gives off very little heat energy to the surrounding machine structure
- Very technically involved:
  - Project planning
  - Cooling channels in the primaries
  - Cooling unit required
  - Hoses for water supply
- Operating the linear motor without water cooling leads to power losses
- Expensive

Water cooling with thermal encapsulation

The primary is encapsulated in a cooling jacket and practically completely separated from the surrounding machine structure. The jacketing is filling with cooling channels.

Features of this system:

- Very high cooling capacity
- Thermal encapsulation of the motor from machine structure; that is, no thermal expansion
- Very technically involved:
  - Project planning
  - Thermal encapsulation of the primary
  - Cooling channels in the enclosure
  - Cooling unit required
  - Hoses for water supply
- Large unit volume
- Operation without water cooling leads to power losses
- Very expensive

2.7.3 Accessories

To optimally carry out their tasks, linear drive systems require a few peripheral components, which are listed in the following section.

Linear guide system

The linear guide system has the following tasks:

- Carry and guide customer loads
- Handle magnetic forces between the primary and secondary
- Guide the measuring system
- Secure the air gap

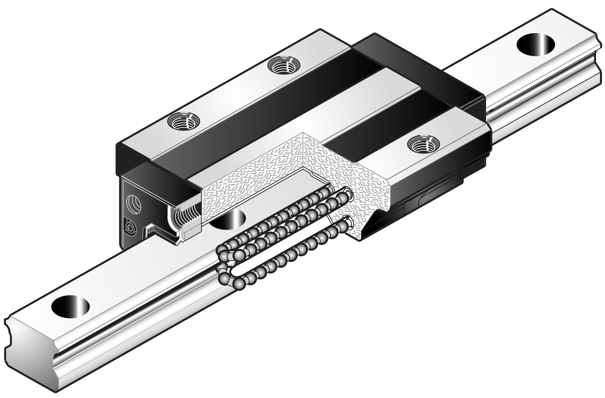

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Fig. 35: Linear guide system

Selection criteria for linear guide systems:

- High accelerations
- High travel speeds
- Intense load changes
- Low noise development
- Handle overhung loads resulting from heat expansion

Various guide systems are used depending on the application and requirements:

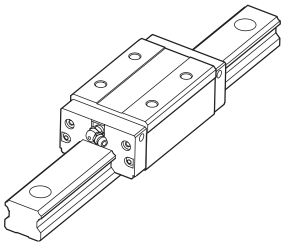

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Fig. 36: Guide with rolling elements

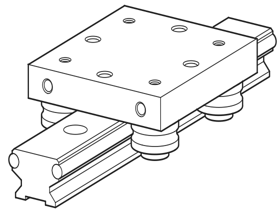

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Fig. 37: Guide with track rollers

These guide systems are only examples. The design of the guide system can change depending on the application. Generally, the customer decides which guide system to use.

Buffers/shock absorbers

The operation of linear motor systems produces high kinetic energies. We highly recommend the use of buffers and shock absorbers for limiting the travel area to prevent greater damage in case of a problem. These components reduce the kinetic energy in the case of a drive system malfunction and product the system from damage.

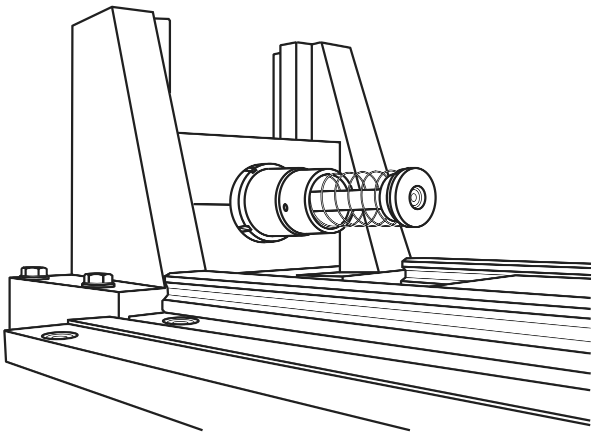

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Fig. 38: Limit switch damper

SEW-EURODRIVE cannot offer buffers or shock absorbers due to the many various applications. Contact the respective component manufacturers.

The features of puffers and shock absorbers are listed below:

Buffers

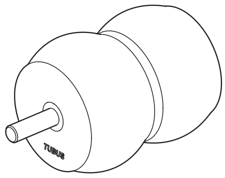

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Fig. 39: Buffer

- Simple design
- Affordable
- No rebound of the contact mass

Shock absorbers

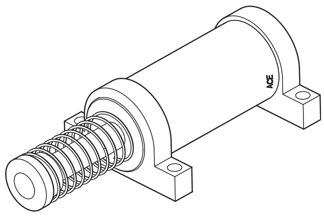

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Fig. 40: Shock absorber

- High energy-absorption capacity
- Effective reduction of kinetic energy
- No rebound of the contact mass
- Low reactive forces on the moved weight and the surrounding structure

Cable carriers and cables

The extremely flexible cables in cable carriers provide power and data to mobile users. The use of extremely flexible cables in the cable carriers has persisted in many applications and is also used for linear motors.

There are special requirements due to the following:

- High accelerations
- Long travel distances, in part
- Large, unsupported distances, in part

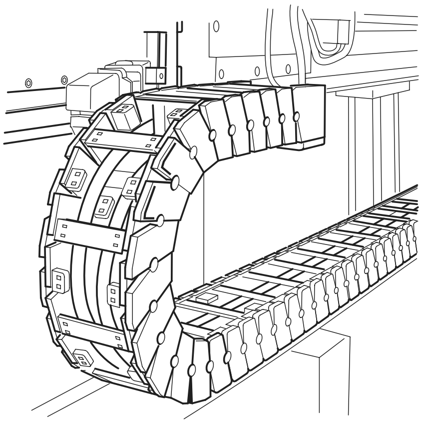

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Fig. 41: Cable carrier

Selection criteria

For applications with unsupported cable carriers, that is, where the carrying run of the cable carrier does not touch the return side, the critical factor is acceleration rather than the traveling velocity. High accelerations cause the cable carrier to vibrate and consequently shorten its service life.

Further criteria to take into account when selecting cables, in additional to the usually high dynamic properties:

- Bending radii
- Suitability for cable carriers
- Shielded motor cable with separate shielding for temperature sensor → hybrid cable
- Encoder cable twisted in pairs and shielded
- EMC-compliant plug connectors
- Do not select cables that are too large → weight reasons
- Arising currents → cable cross section
- System- and country-specific regulations

Moving the secondaries in a linear system is advantageous, as the cables are not moved.

2.8 Brakes for rotary servomotors

This section provides an short overview of the brake systems used in SEW servomotors. This information in no way replaces manufacturer-specific notices or country- or system-specific safety regulations. These must be accounted for during project planning:

You can find additional information on brake systems for servomotors from SEW-EURODRIVE in the volume "SEW Disc Brakes" from the series "Drive Engineering – Practical Implementation" on in the valid geared servomotor catalogs.

On request, motors and geared motors can be supplied with an electromechanical brake. This brake is an electromagnetic disk brake with a DC coil that releases electrically and brakes using spring force. Consequently, the brake is applied if the power fails.

Depending on the application, the motor brake must:

- Stop loads, such as the hoist axis
- Perform an emergency stop
- Stop machine units, such as the feed slide
- Secure against unintentional shifting

You will find information about brake systems as used by SEW-EURODRIVE in the following section.

2.8.1 Spring-loaded brake as a holding brake

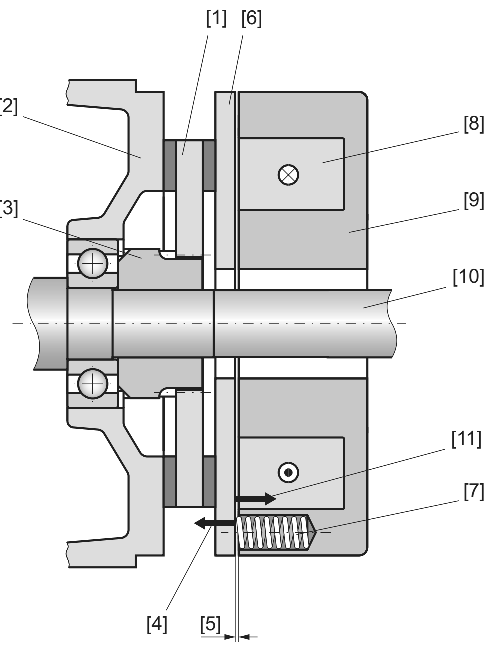

Fig. 42: Basic design of the SEW holding brake

[1]	Brake disc	[7]	Brake spring
[2]	Brake endshield	[8]	Brake coil
[3]	Driver	[9]	Brake coil body
[4]	Spring force	[10]	Motor shaft
[5]	Working air gap	[11]	Electromagnetic force
[6]	Pressure plate		

2.8.2 SEW brake with working capacity

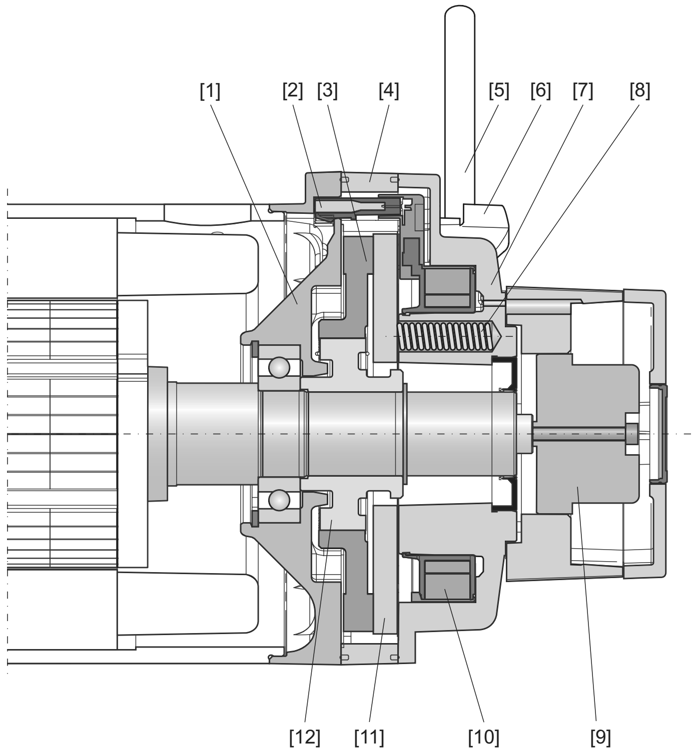

Fig. 43: Design of the brake with RH1L resolver for CM71 .. 112

[1]	Brake endshield	[7]	Magnet
[2]	Power socket	[8]	Brake spring
[3]	Brake disc	[9]	RH1L resolver
[4]	Guide ring	[10]	Brake coil
[5]	Hand lever	[11]	Pressure plate
[6]	Releasing lever	[12]	Driver

The SEW-EURODRIVE spring-loaded brake is an electromagnetic disk brake with a DC coil that releases electrically and brakes using spring force. The brake is compliant with many safety requirements as it is applied in a power failure.

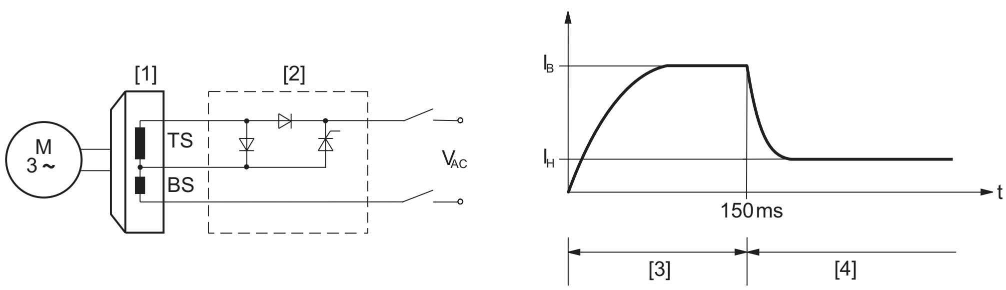

Fig. 44: Switching principle

[1]	Brake	BS	Accelerator coil
[2]	Brake control	TS	Coil section
[3]	Acceleration	BS+TS	Holding coil
[4]	Holding	I_B	Acceleration current
		I_H	Holding current

In contrast to other disc brakes with a DC coil, the brakes from SEW-EURODRIVE operate with a two coil system.

When deenergized, the pressure plate is forced against the brake disc by the brake springs. In other words, the motor is braked. If suitable voltage is applied to the brake coil, the magnetic force overcomes the spring force of the brake springs, bringing the pressure plate into contact with the brake coil body. The brake disc is free and the motor can turn.

A special brake control system ensures that only the accelerator coil is switched on first, followed by the holding coil (entire coil). The strong impulse magnetization of the accelerator coil, triggered by a high acceleration current, produces a very short response time. This is especially important for large brakes as the saturation point is not reached. The brake disc moves clear very quickly and the motor starts up with hardly any braking losses.

SEW-EURODRIVE offers the right brake rectifier for almost every application, depending on the purpose and location. Refer to the appropriate documentation for more information.

2.8.3 Permanent-field holding brake

For brakes, the magnetic field of the permanent magnet is conducted over the internal and external pole to the armature. The armature is pulled by the magnetic field, as the magnetic force F_M is greater than the spring force F_F. The friction between the rotating armature and the standing poles produces the braking torque.

If the brake coil is energized, a magnetic field is formed whose force F_M compensates for the spring force F_F. The armature detaches from the poles, releasing the brake.

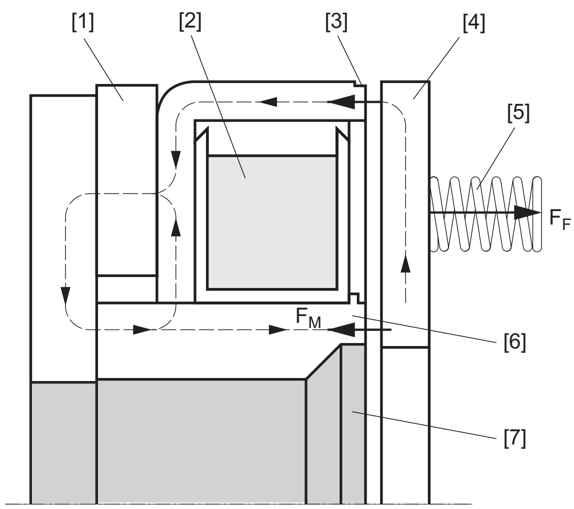

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Fig. 45: Functional principles of the holding brake

[1]	Permanent magnet	F_M	Force of magnetic field
[2]	Brake coil	F_F	Spring force
[3]	External pole		
[4]	Armature		
[5]	Spring		
[6]	Internal pole		
[7]	Rotor		

2.9 Brakes for linear motors

The design of the brakes for linear motors varies widely depending on the motor system or application and the resulting requirements.

Refer to the documentation and literature from the respective supplier.

For linear motor, the brake has the function of a holding brake. The holding brake and the guide system must match. In other words, you must coordinate with the manufacturer of the guide system.

Due to the traveling velocities that are usually high, particularly high requirements are placed on breaks for linear systems:

- Light, compact design
- High power density
- Fast application and release

Brake systems with various properties are used depending on the application. The following list provides a short overview of the properties of the most comment brake systems:

Electric motor-driven brake

- High holding forces
- Very compact and light
- Cannot be integrated
- Brake applies slowly
- Brake must be actively applied with current

Electromagnetic brake

- Brake applies and releases very quickly; well suited for short cycle times
- High holding forces
- Robust design
- Spring-loaded brake as emergency brake

Pneumatic brake

- High holding forces
- Very compact, light, and able to be installed to save space
- Inexpensive, large selection
- Suited for medium cycle times
- Connection to a pneumatic system required

Pneumatic breaks are available in various designs:

- Brakes that are opened with pressure (pneumatic with spring-loaded brake)
- Brakes that are closed with pressure

Mounting brakes on SL2-Advance System and SL2-Power System linear motors

Two examples explain the integration of various brake systems with SL2 motors.

Brakes with dimensions according to DIN 645-1; series 1M, and 1L for profile rail roller bearing guides can be used in the SL2-Advance system and SL2-Power system designs. Brakes can be mounted on both the fixed bearing and floating bearing end.

One particular advantage of this system is that the brake at the floating bearing end is mounted to the cooling unit together with the guide carriage and consequently, is not thermally loaded.

Compact brake designs, such as the pneumatic brakes, can be integrated between the guide carriages.

Longer brakes can be mounted on the end of the cooling unit; see figure 46.

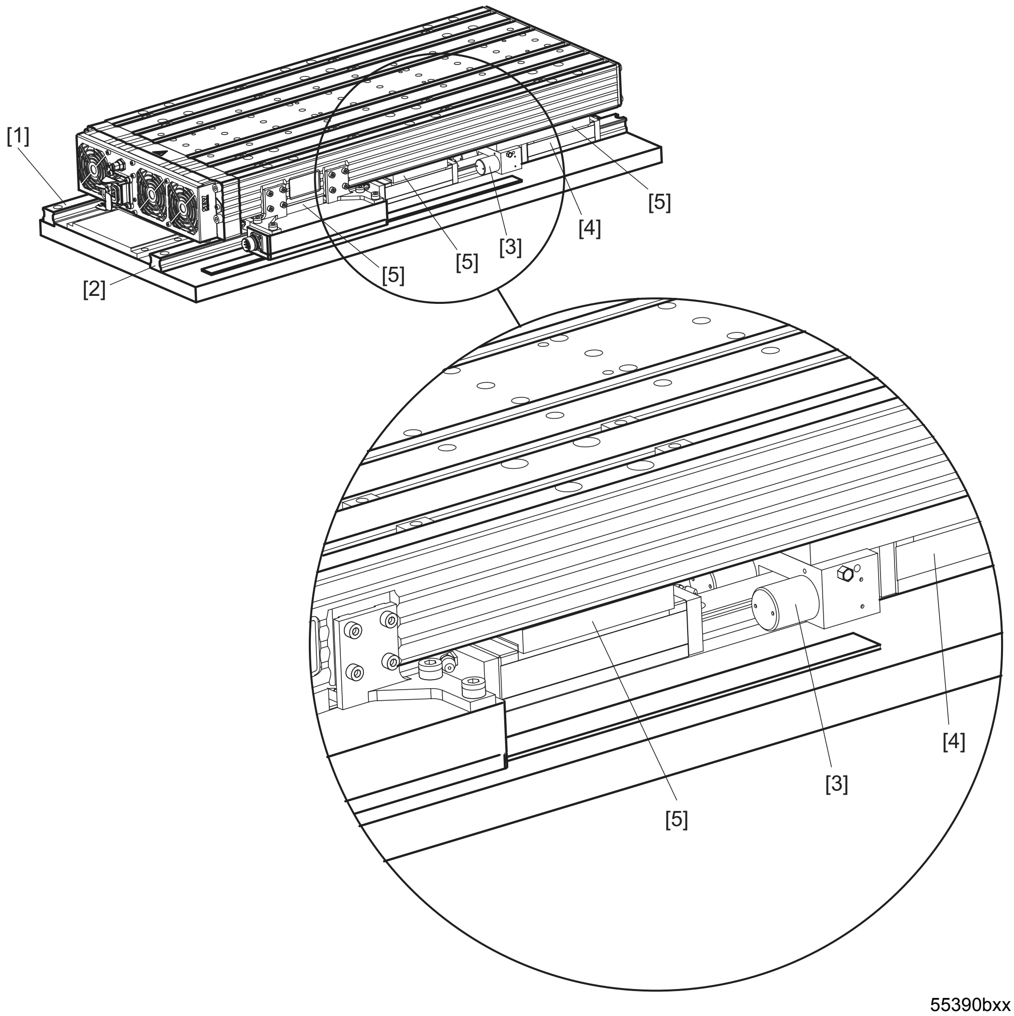

Fig. 46: SL2-Power linear motor with pneumatic brake from SEW-EURODRIVE

[1]	Floating bearing end	[4]	Guide carriage
[2]	Fixed bearing end	[5]	Adapter plate
[3]	Pneumatic brake		

You can find additional information on installing break systems in the SL2 linear motor series from SEW-EURODRIVE in the product documentation or contact SEW-EURODRIVE directly.

3 Encoder Systems

As illustrated in the previous chapters, it is possible to operate a servomotor with an encoder system. The encoder systems most used in servo technology and by SEW-EURODRIVE are described in the following sections.

3.1 Incremental encoders

3.1.1 Incremental encoders with TTL and HTL signals

Incremental encoders convert the speed into a direct number of electrical impulses. This is performed by means of an incremental disk incorporating radial slits permitting the passage of light. These slits are scanned by optoelectronic means. This principle is illustrated in figure 47. The resolution of the incremental disk is determined by the number of slits.

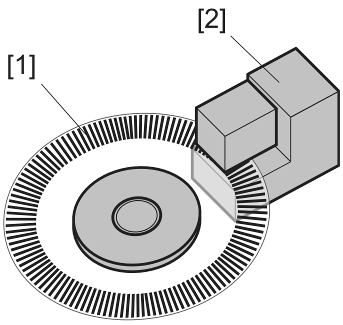

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Fig. 47: Incremental encoder

[1] Incremental disk

[2] Sampling unit

Design and functional principle

Usually, these encoders have two tracks and one index signal track. Inverting the signals results in a total of six signals. Two light barriers are arranged at right angles to one another in the encoder. These supply two sequences of pulses on tracks A (K1) and B (K2). Track A (K1) is 90° ahead of B (K2) when the encoder is turning clockwise (to the right as viewed looking onto the motor shaft). This phase shift is used for determining the direction of rotation of the motor. The zero pulse (one pulse per revolution) is registered by a third light barrier and made available on track C (K0) as a reference signal.

For TTL encoders, tracks A (K1), B (K2), and C (K0) are negated in the encoder and made available on tracks $\overline{A}$ ($\overline{K1}$), $\overline{B}$ ($\overline{K2}$) and $\overline{C}$ ($\overline{K0}$) as negated signals.

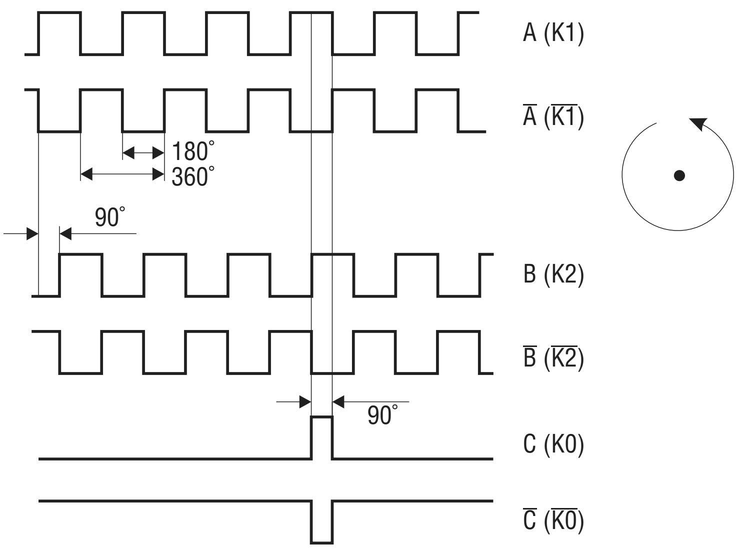

Fig. 48: TTL signals with zero track, with inverted signals HTL signals with zero track, without inverted signals

There are two kinds of signal levels for incremental encoders:

- TTL (**T**ransistor-**T**ransistor-**L**ogic)
  The signal levels are V_{low} ≤ 0.5 V and V_{high} ≥ 2.5 V. The signals are transferred symmetrically and evaluated differentially. In other words, a voltage level difference of 5 V is available for distinguishing between low signals and high signals. Therefore, they are not sensitive to common mode interference and have a good EMC behavior. Signal transmission uses the RS422 protocol. Due to these properties, TTL encoders are mostly used with incremental encoders.

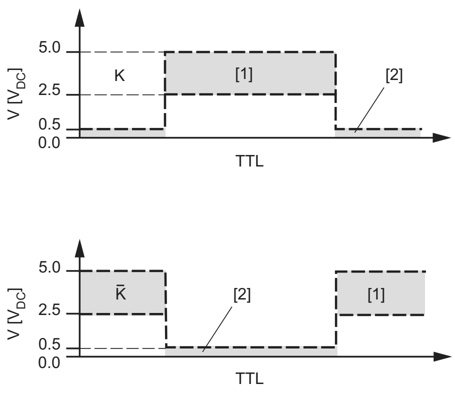

Fig. 49: TTL signal level

[1] Area "1"
[2] Area "0"

- HTL (**H**igh voltage-**T**ransistor-**L**ogic)
  The signal levels are $V_{low} \leq 3$ V and $V_{high} \geq V_{Bminus}$ (= 3.5 V). HTL encoders are evaluated without the inverted tracks; differential signal evaluation is not possible. Consequently, HTL signals are susceptible to common mode interference, which can negatively affect the EMC behavior.

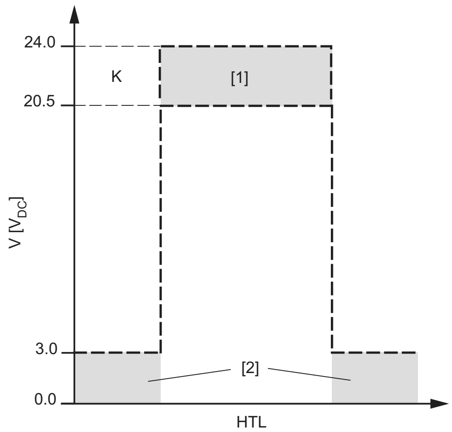

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Fig. 50: HTL signal level

[1] Area "1"

[2] Area "0"

Inverted HTL signals generally cannot be attached to the encoder input of the servo inverter as the input levels can be overloaded and therefore destroyed.

3.1.2 Incremental encoders with sin/cos tracks

Design and functional principle

Sin/cos encoders, also called sinusoidal encoders, supply two sinusoidal signals, offset by 90°. For this, the number of sine waves (same as the number of impulses), zero passages, and amplitudes (arc tangent) are evaluated. Using these values, the speed can be determined with a high resolution. This is especially advantageous if a large setting range and small speeds must be exactly met.

Usually, sin/cos encoders have two tracks and one index signal track. Inverting the signals results in a total of six signals. The 90° offset sine signals are on tracks A (K1) and B (K2). One sine half-wave per revolution is provided at channel track C (K0) as the zero pulse. Tracks A (K1), B (K2) and C (K0) are inverted in the encoder and made available on tracks A* (K1*), B* (K2*) and C* (K0*) as inverted signals.

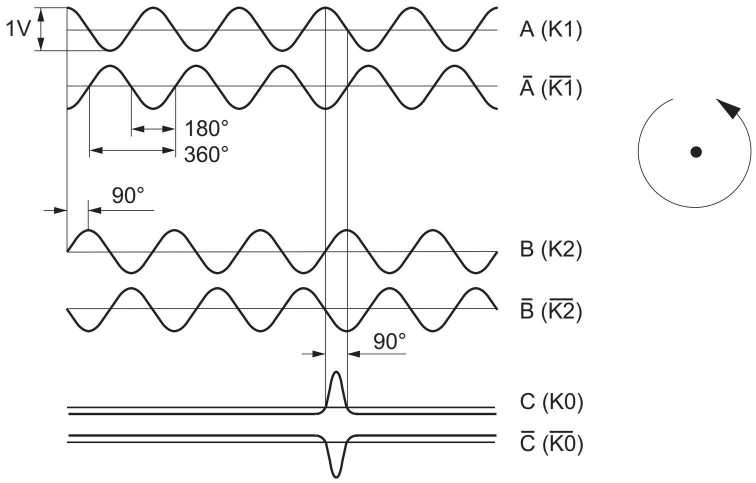

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Fig. 51: Sin/cos signals with zero track and inverted signals

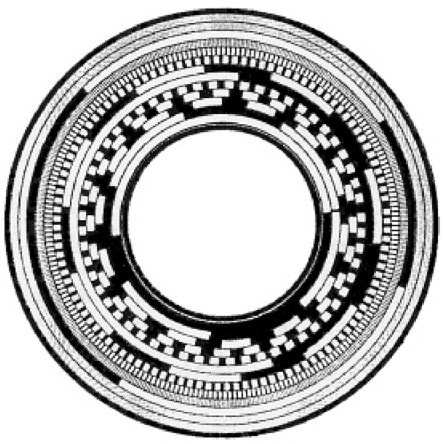
The sin/cos signals are usually superimposed on a DC voltage of 2.5 V. They have a peak-to-peak voltage of V_{SS} = 1 V. Thus, the zero passages are avoided during signal transmission. As the sin/cos signals are transferred symmetrically and evaluated differentially, they are not sensitive to asymmetric interference and have a good EMC behavior.

3.2 *Absolute value encoders*

In the last few years, combination encoders have become established in the market place in addition to resolvers. These encoders are sin/cos encoders with absolute value information. In addition to the current speed of the motor, they provide absolute value information and offer technical and financial advantages if an absolute value encoder is required.

3.2.1 Absolute encoders with SSI interface and sin/cos signals

The absolute value information is generated by a code disk with Gray Code that is generally optically scanned. In doing so, every angle position has a unique code pattern assigned to it, making it possible to determine the absolute position of the motor shaft. The special feature of Gray Code is that only one bit changes with the transition to the next angle step. In other words, the possible reading error is only one bit.



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Decimal	Gray Code
0	0000
1	0001
2	0011
3	0010
4	0110
5	0111
6	0101
7	0100
8	1100
9	1101
10	1111
11	1110
etc.	etc.

Fig. 52: Code disk with Gray Code

This kind of encoder is a single-turn encoder because the absolute position of the motor shaft can only be determined with one revolution. In addition to single-turn designs, there are also multi-turn encoders that determine the absolute position with multiple revolutions.

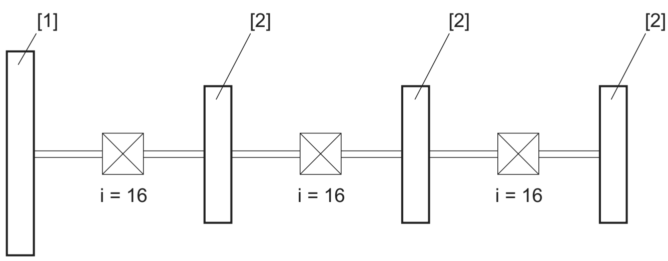

Fig. 53: Multi-turn encoder design

[1] Code disk for recording the winding position
[2] Code disk for recording the number of revolutions

In addition to the code disk for recording the winding position, multi-turn encoders have other code disks to be able to record the number of revolutions absolutely. These code disks can be each coupled with each other via a gear unit stage with the reduction ratio i=16. With three additional code disks (usual value), 16 x 16 x 16 = 4096 revolutions can be absolutely resolved. The number 16 comes from 16 bits in binary format (a word).

3.2.2 Absolute encoders with HIPERFACE® interface

Design and theory of operation of HIPERFACE® encoders

HIPERFACE®[1)] encoders are typically combination coders that are also used by SEW-EURODRIVE. In addition to a sin/cos signal for speed recording and absolute value information, these encoders also have an electronic nameplate in which data such as drive data can be stored. This makes startup easier and reduces possible user input errors, as the user does not need to input any drive data.

There are two different versions of HIPERFACE® encoders:

1. Single-turn HIPERFACE® encoders
2. Multi-turn HIPERFACE® encoders Using the code disk with Gray Code that is coupled with a small, multi-stage encoder, the absolute position can be output for 4096 motor revolutions.

Features of the HIPERFACE® encoder:

- Operating voltage 7–12 V
- Operating temperature up to 115°C maximum
- Maximum cable length 100 m
- 10-core cable
- Internal memory offers "electronic nameplate" option
- Single-turn and multi-turn versions
- Optical evaluation of absolute value (single-turn)
- Reference travel no longer required for restart (for multi-turn)
- Both absolute value and sin/cos tracks (1024 sin and cos periods/revolution) integrated
- Analog signal transfer; resolution of the 1024 sin/cos periods takes place in controller
- High level of resistance against electromagnetic radiation
- Mounted encoder as stand-alone solution (synchronous encoder)
- Electronic adjustment of commutation
- Process data channel processes data in real time
- Small dimensions

1) HIPERFACE stands for "High Performance Interface" and is an interface that was developed by the company Sick Stegmann GmbH.

At the beginning of the startup process, the absolute value encoder component optically records the absolute position of the rotor. The servo inverter reads this position information via an RS485 connection (parameter channel) and sets a counter status. Based on this absolute value, the position changes are recorded using the tracks of the sin/cos encoder. These changes are transmitted over the process data channel to the servo inverter in analog form. Additional absolute position queries are only performed periodically to check validity.

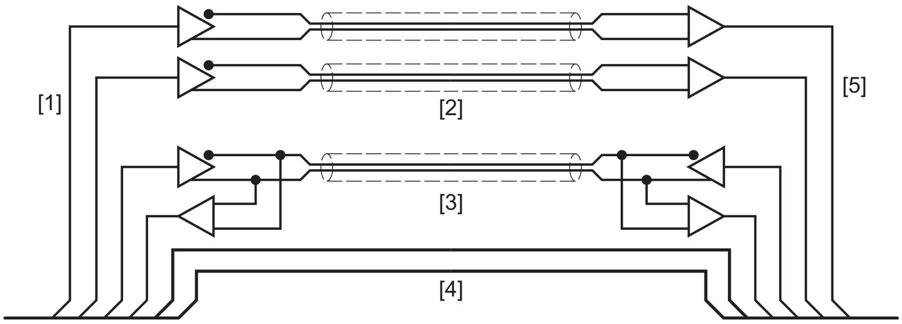

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Fig. 54: Information flow

[1] Motor feedback
[2] Process data channel
[3] RS485 parameter channel
[4] Supply voltage
[5] Servo inverter

The servo inverter here is a MOVIDRIVE® MDX61B with the appropriate encoder option. The servo inverter with the HIPERFACE interface receives position information as well as the time for which the position is valid via the parameter channel. At the same time, the process data channel continuously receives and counts the incoming analog (sin/cos) signals.

The encoder is available in single-turn or multi-turn versions. Single-turn means that the absolute position information always relates to one revolution only. The multi-turn encoder version can additionally provide absolute zero position information over multiple revolutions (up to 4096) by means of subsequent code disks. Consequently, an encoder overflow takes place after 4096 revolutions that is still counted in the non-volatile RAM of the MOVIDRIVE®. Up to 256 encoder overflows are saved. If the voltage at the supply pins drops below a threshold (for example, in a power failure), NVSRAM detects this and saves the data so that it is not lost in the event of a power failure.

When the encoder is turned back on, the following is output from the NVRAM in the servo inverter:

- The absolute value within an overflow, a maximum of 4096 × 4096
- The number of overflows, from 0 to 255

If the drive that is close to an overflow is moved beyond the encoder overflow point when the supply voltage is removed, a discrepancy exists at restart between the recorded and the stored absolute values. The encoder electronics then corrects the stored values automatically with the recorded ones.

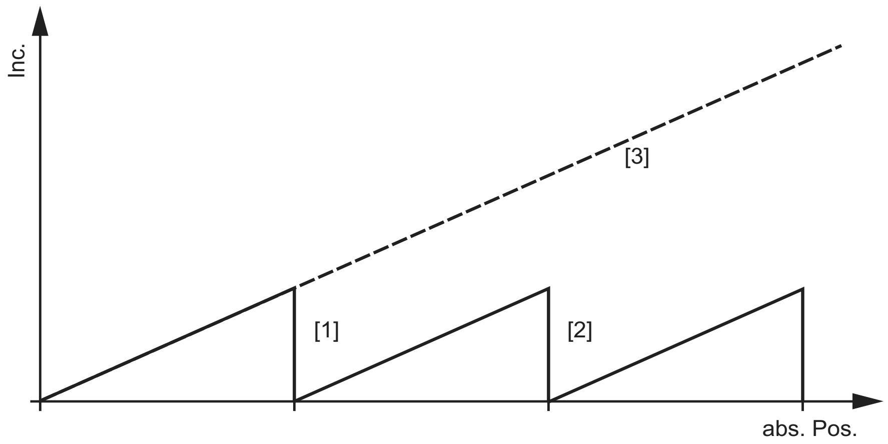

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Fig. 55: Encoder overflow

[1] First encoder overflow
[2] Second encoder overflow
[3] Absolute value seen by user

The encoder overflows are counted in the servo inverter and thus the absolute position can be determined.

The user does not see the actual encoder overflows; they are saved in the servo inverter. Consequently, the HIPERFACE® encoder is a real absolute value encoder.

3.2.3 Resolvers

The most used encoder system for synchronous servomotors is the resolver. A two-pole resolver can determine the absolute position of the motor shaft within one motor revolution. The speed and the absolute position are derived from the resolver signal each revolution.

Design and theory of operation

The resolver consists of two function units, the transformer (stator) and the rotary transformer (rotor).

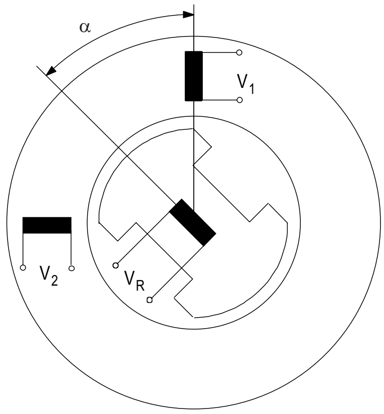

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Fig. 56: Schematic design of the resolver

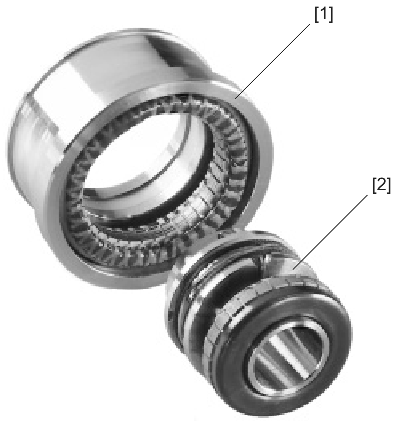

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Fig. 57: Resolver

[1]	Stator of the resolver (transformer)
[2]	Rotor of the resolver (rotary transformer)

The servo inverter supplies a high frequency signal with a constant amplitude and frequency. This high frequency signal is transferred over the transformers to the rotor of the rotary transformer.

The rotation of the resolver rotor induces the rotor-position-dependent voltages into the stator winding of the rotary transformer.

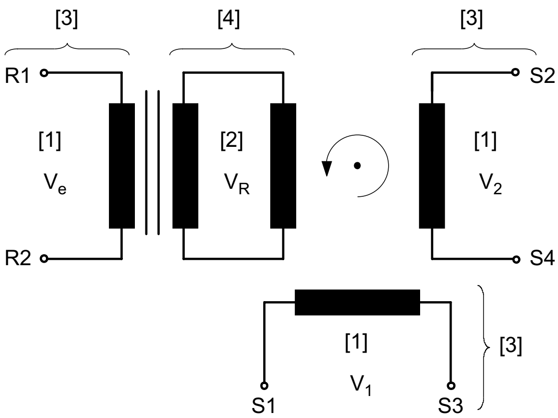

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Fig. 58: Equivalent circuit diagram of a resolver

[1]	Stator	[3]	Fixed
[2]	Rotor	[4]	Rotating

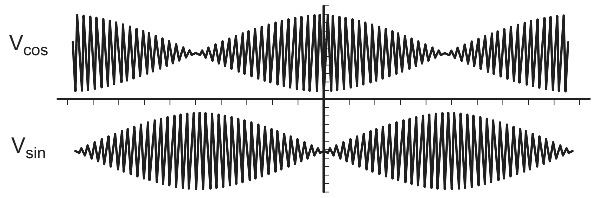

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Fig. 59: Output voltages V_{cos} and V_{sin} of the resolver

The characteristics of the signals are calculated as follows:

$V_{ref} = A \times \sin(\omega_{Excite} \times t)$

$V_{cos}(t) = A \times ü \times \sin(\omega_{Excite} \times t) \times \cos(p \times \alpha)$

$V_{sin}(t) = A \times ü \times \sin(\omega_{Excite} \times t) \times \sin(p \times \alpha)$

$p \times \alpha = \arctan(V_{sin} / V_{cos})$

V_{ref}	Reference voltage
V_{cos}	Output voltage 1 of the stator
V_{sin}	Output voltage 2 of the stator
A	Peak value of the input voltage
ω_{Excite}	Angular frequency of V_e
α	Rotor angle
ü	Ratio
p	Number of pole pairs of the resolver

The technical advances in the area of semiconductors have made today's high-quality analog/digital converters available at a low price. These analog/digital converters make it possible to discretely design very good resolver evaluations and to achieve an even higher resolution of the measured signals than with the integrated resolver evaluation modules used in the past.

Modern resolver evaluations no longer work with the "coasting method". Instead, they use the "scanning measuring method". Here, a DSP generates a rectangular signal, which an excitation switch helps to convert into a sinusoidal reference voltage that supplies the resolver; see figure 60.

Depending on the position of the rotor, the amplitudes of the voltages V_{sin} and V_{cos} change and are each supplied to the A/D converter via a differential amplifier. The differential amplifiers filter out high frequency interference on the isolated track signals V_{sin} and V_{cos} and output a voltage with ground reference on each of the inputs of the A/D converter.

The A/D converter scans both of the envelopes at the same time as the excitation voltage of the maximum value, converts these analog signals into digital information and transfers them to the DSP; see figure 59 for more information. It then determines the current position from the scanned track signals V_{cos} and V_{sin}.

The current mechanical position can be easily determined from the scanned track signals.

$p \times \alpha = \arctan(V_{sin} / V_{cos})$

In this way, a new position value is determined for every period of the excitation signal. This data is transferred over the DPR interface to the microcontroller of the axis controller, which requires the information to control the axis.

The following figure gives a overview of the principle hardware structure of a resolver evaluation that works according to the scanning method.

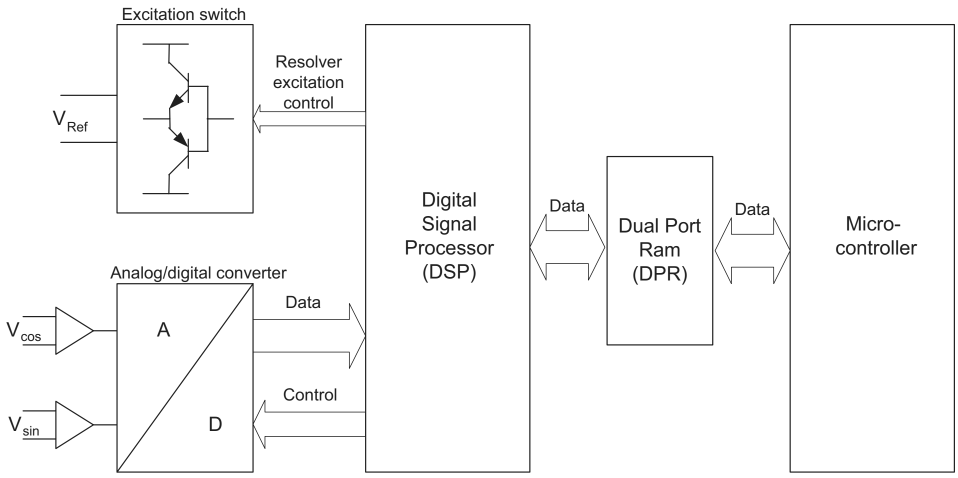

Fig. 60: Hardware resolver evaluation (simplified representation)

3.3 Comparison/selection guide for resolvers, sin/cos encoders, TTL encoders

The following table displays the most important features of the encoder systems for rotary servomotors that have been introduced and provides project planning with a selection guide for selecting the encoder system. Encoder systems as used by SEW-EURODRIVE have been used as an example.

Encoder system [SEW type] Features	Resolver [RH1M, RH1L]	HIPERFACE® encoder (sin/cos encoder with absolute value) [AS1H, ES1H, AS3H, AS4H, AV1H]	Sin/cos encoder [ES1S, ES2S, EV1S]	Incremental encoder [ES1R, ES2R, EV1R]
Resolution	Determined by the resolver evaluation: up to 16 bits/revolution	– 1024 sin/cos periods (for speed control) – 32768 steps/revolution (for positioning)	1024 sin/cos periods	1024 pulses/revolution
Permitted temperature range	Approx. –55 °C to +150 °C	– –20 °C to +115 °C (AS1H, ES1H) – –20 °C to +85 °C (AS3H, AS4H, AV1H)	–20 °C to +85 °C	–20 °C to +85 °C
Mechanical influences	– Shock 100 g / 11 ms – Vibration 20 g / 10 – 50 Hz	– Shock 100 g / 10 ms – Vibration 20 g / 10 – 2000 Hz	– Shock 300 g / 1 ms – Vibration 10 g / 10 – 2000 Hz	– Shock 100 g / 6 ms – Vibration 10 g / 10 – 2000 Hz
Application	For speed control and determining the rotor position within one motor revolution as well as "incremental" positioning	For speed control and determining the rotor position and absolute position	For speed control and "incremental" positioning	For speed control and "incremental" positioning
Suitable for	– Synchronous servomotors – Asynchronous servomotors (on request)	– Synchronous servomotors – Asynchronous servomotors	Asynchronous servomotors	Asynchronous servomotors
Add-on conditions	Built-in encoder	– AS1H, ES1H: built-in encoder (synchronous servomotors) – AS3H, AS4H, AV1H: add-on encoder (asynchronous servomotors)	Add-on encoder	Add-on encoder
Other features	Very mechanically robust	– High resolution of speed information possible through interpolation of sin/cos signal – Simple startup due to electronic nameplate	High resolution of speed information possible through interpolation of sin/cos signal	Simple encoder system for standard applications

3.3.1 Technical data of the encoders used by SEW-EURODRIVE

Encoder type	Assembly	To be attached to	Signal	Supply [V]
Incremental encoders				
ES1H	Built-in encoder, integrated with synchronous servomotor	DS/CM synchronous servomotors	1 V sin/cos HIPERFACE® S single-turn with built-in EEPROM for saving the electronic name plate	7 .. 12
ES1T ES2T	Spreadshaft	• DT/DV AC motors • CT/CV asynchronous servomotors	5 V TTL	5
ES1S ES2S			1 V sin/cos	10 .. 30
ES1R ES2R			5 V TTL	
ES1C ES2C			24 V HTL	
EV1T	Coupling with solid shaft		5 V TTL	5
EV1S			1 V sin/cos	10 .. 30
EV1R			5 V TTL	
EV1C			24 V HTL	
RH1M	Hollow shaft	CM synchronous servomotors	Resolver signals, 2-pole	7
Absolute value encoders				
AV1H	Coupling with solid shaft	• DT/DV AC motors • DS synchronous servomotors • CT/CV asynchronous servomotors	1 V sin/cos HIPERFACE® S multi-turn with built-in EEPROM for saving the electronic name plate	7 .. 12
AV1Y			M SSI 1 V sin/cos	10 .. 30
AS1H	Built-in encoder, integrated with synchronous servomotor	DS/CM synchronous servomotors	1 V sin/cos HIPERFACE® S multi-turn with built-in EEPROM for saving the electronic name plate	7 .. 12
AS2H AS3H	Spreadshaft	• DT/DV AC motors • CT/CV asynchronous servomotors	1 V sin/cos HIPERFACE® S multi-turn with built-in EEPROM for saving the electronic name plate	7 .. 12
Resolvers				
RH1M	Hollow shaft	CM synchronous servomotors	Resolver signals, 2-pole	7
RH1L		Synchronous servomotors with brake		

3.4 Direct travel distance measuring system for linear servomotors

As illustrated in section 2.7, a measuring system is required for the operation of synchronous linear motors to detect the position of the primary. Using the position, the velocity is derived in the relevant servo inverter and positioning is carried out.

There are different criteria for the selection of the appropriate encoder system depending on the application:

- Maximum velocity
- Maximum travel distance
- Resolution according to accuracy requirements
- Contamination level
- EMC conditions

3.4.1 Design and theory of operation of optical travel distance measuring systems

An optical travel distance measuring system consists of a measuring gauge made of glass or steel mounted on the track and a scanning unit that travels over the track. The scanning unit contains a light source, photo elements and optical filters for better recording. The light emitted by the light source hits the measuring gauge and is reflected according to the applied pitch and detected by the photo elements from which evaluation electronics generate an incremental signal.

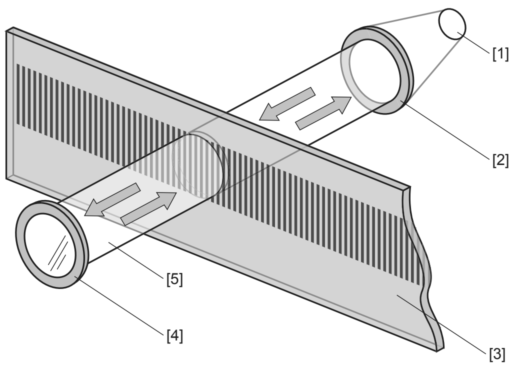

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Fig. 61: Schematic representation an optical measuring system

1	Light source and photo element
2	Lens
3	Scanning plate
4	Reflector
5	Light waves

Depending on the resolution, the optical travel distance measuring system may function differently in the following ways:

- Display principle with a line graduation of 20 – 100 µm
- Interference principle with a line graduation of 4 – 8 µm

Depending on the usage conditions and environmental conditions, different optical systems designs are used.

Closed systems

- Maximum traveling velocity approx. 2 m/s
- Good protection from environmental conditions
- Mechanical control

Open systems

The system works without mechanical control.

- The scanning unit is attached to the movable part and more or less "floats" above the track (material measure) making the maximum traveling velocity approx. 8 m/s
- Almost no protection from environmental conditions

3.4.2 Design and theory of operation of magnetic travel distance measuring systems

Magnetic travel distance measuring systems consist of:

- A magnetic tape
- A sensor

The magnetic tape is attached to the track as a measuring tape. The sensor that is attached to the primary travels over this measuring tape.

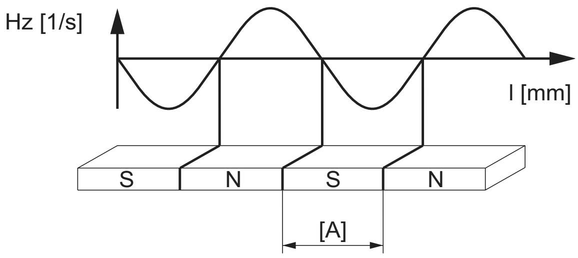

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Fig. 62: Magnetic distance measuring system

[A] Resolution

The sensor measures the changes of the magnetic field strength via a travel motion, which evaluation electronics use to generate a sinusoidal signal. The phase-shifted configuration of the two sampling units within a sensor generates sine or cosine signals.

The sine signals of the sampling element can be resolved higher using interpolation. Optional electronic switches integrated in the encoders can convert these sine signals into commonly used interface signals such as RS422.

These measuring tapes are also available with a magnetized code for the absolute value. Reference travel is not required after startup for encoder systems with absolute value information. Absolute value encoders convert the signal into an SSI protocol.

The following properties of magnetic travel distance measuring systems must be taken into account during project planning:

- Resolution: Usually 5000 µm/sine cycle
- Accuracy: Approx. 300 µm/m
- Travel velocities up to approx. 6 m/s possible
- Not sensitive to contamination
- Not mechanically sensitive
- Interface: SSI, HIPERFACE®

3.4.3 Design and theory of operation of inductive travel distance measuring systems

Inductive travel distance measuring systems work according to the principle of variable reluctance. Markings on a metallic measuring tape deflect a magnetic field generated by a control unit. These field changes are detected by evaluation electronics and converted to sine signals. The phase-shifted configuration of the two sampling units within a sensor generates sine or cosine signals.

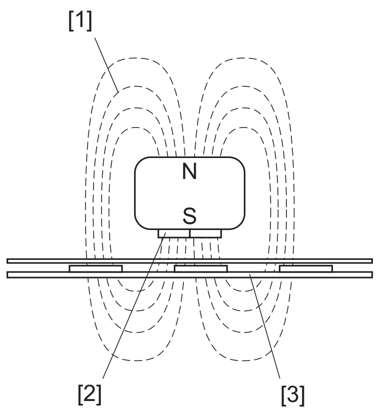

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Fig. 63: Schematic representation an inductive measuring system

[1] Magnetic field lines
[2] Magnetic sensors
[3] Measuring tape cross-section

The measuring tape on the track is crucial to the accuracy of the measurement. It consists of several layers: The core is a metal strip in which the markings are etched very precisely. These measuring tapes are also available with a reference mark. Depending on the design of the length-measuring system, the reference signal is partially recorded by a separate sensor. This metal strip is embedded between the carrier and cover tape.

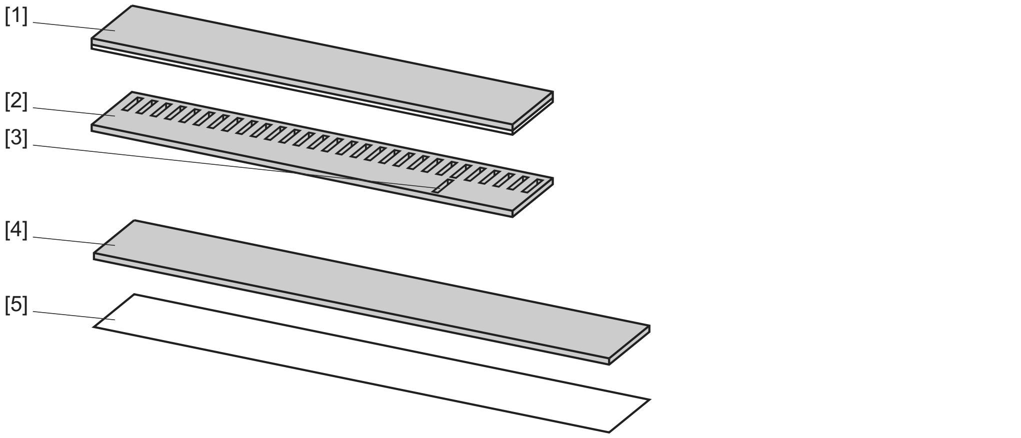

Fig. 64: Design of a measuring tape in layers

[1]	Cover tape	[4]	Steel carrier tape
[2]	Pitch	[5]	Adhesive layer
[3]	Reference marks		

Optional evaluation electronics are available for inductive measuring systems for converting the sine and cosine signals into a TTL signal.

The following properties of inductive travel distance measuring systems must be taken into account during project planning:

- Traveling velocities up to approx. 20 m/s
- Resolution: 1000 µm/sine cycle (sin/cos signal)
  5 – 50 µm (TTL signal)
- Accuracy: Approx. 10 µm/m
- Usually IP66 design
- Not sensitive to contamination

3.5 Definitions

Term/abbreviation	Definition/explanation
HIPERFACE®	**Hi**gh **Per**formance Inter**face**. Registered trademark of the company Sick Stegmann GmbH.
EMC	**E**lectro**m**agnetic **c**ompatibility
TTL	**T**ransistor-**T**ransistor-**L**ogic
HTL	**H**igh voltage-**T**ransistor-**L**ogic
SSI interface	**S**ynchronous **S**erial **I**nterface
Single-turn encoder	Absolute position specification over one revolution
Multi-turn encoder	Absolute position specification over multiple revolutions
A/D converter	**A**nalog/**d**igital converter
SRAM	**S**tatic **R**andom **A**ccess **M**emory
NVSRAM	**N**on-**V**olatile **S**tatic **R**andom **A**ccess **M**emory
EEPROM	**E**lectrically **E**rasable **P**rogrammable **R**ead **O**nly **M**emory
DSP	**D**igital **S**ignal **P**rocessor
DPR interface	**D**ual **P**ort **RA**M interface
Reluctance	Magnetic resistance

4 Servo Inverters

4.1 General information on servo inverters

Rationalization and automation requirements have grown for modern production machines and units, causing the requirements for powerful servo inverters to rise accordingly.

Consequently, servo drives no longer work as simple auxiliary drives or drives for infrequent speed variation. Instead, they carry out important machine functions using complex technological functions such as phase-synchronous operation, electronic cam, touch probe processing, torque control, and so on, that were previously subject to mechanical solutions.

Powerful servo inverters feature:

- High control qualities
  - Rotational accuracy
  - Low speed deviation
  - Low position deviation
- High dynamic properties
  - Short transient recovery times for setpoint and load changes
- Overload capacity:

  Travel cycles with short cycle times and high accelerations require the servo inverter to be able to provide sufficient power. Due to short acceleration times, larger servo inverters with lower overload capacities must be chosen, which causes higher system costs.
- Powerful microcontroller that allows for programming/configuration as desired
- Complex technology functions such as:
  - Electronic cam
  - Phase-synchronous operation
  - Touch probe processing
  - Torque control
- Flexible interfaces:
  - Isolated binary inputs and outputs
  - Analog inputs and outputs
  - Multiple encoder interfaces for different encoder systems, for motor and synchronous encoders
  - Option PCB slot for fieldbus interfaces and control cards, for example
- Additional bus interface for communication with other servo inverters
- Common interface/connection options for operating devices and PCs such as USB and Ethernet
- Additional security features such as "safe stop" connecting terminals according to EN 954-1, category 3
- Large range of permitted supply voltage, 3 × 380 V (–10 %) ... 500 V (+10 %)
- Compliance with EMC classes A and B according to EN 5011
- Connection for braking resistor

4.1.1 The DC link

The power section of a servo inverter is usually based on the principle of the DC link amplifier. The rotating field that forms the torque is generated from this DC link via an inverter bridge. The DC link is usually generated via a B6 diode bridge directly (without a transformer) from the three-phase supply system.

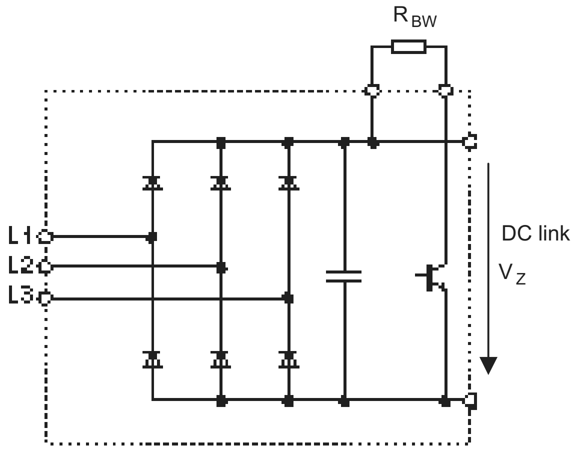

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Fig. 65: Block circuit diagram of the DC link and B6 diode bridge

R_{BR}	Braking resistor
V_Z	DC link voltage [V]

The DC link capacitor store rectified AC voltage as energy buffer. The kinetic energy resulting from the breaking of a drive is converted into electrical energy and is feed back into the DC link. The capacity of the DC link determines the amount of energy it can accept.

Capacitors and other parts are used for the layout of the DC link. The total capacity of all capacitors used in the DC link determines the type of the DC link, which is considerably higher than the total rated capacity. In the trade, DC links with low capacities are called "thin" links and those with high capacities are called "thick" links.

SEW-EURODRIVE combines both kinds of DC links in their servo inverter systems.

	Thin link	Thick link
Principle	Use of: • Metal film capacitors (MKS) • Metallized plastic film capacitors (MKP)	Use of: • Electrolytic capacitors
Advan-tage	No charging connection required.	Can store more energy, especially advantageous for dynamic applications.
	Lower power supply disturbances.	Smaller braking resistor dimensioning.
	Cost savings due to fewer components.	More efficient power exchange between axis modules.
	Space saving due to smaller unit volume.	
	Longer service life of foil capacitors.	

4.1.2 The inverter

The inverter is supplied by the DC link voltage V_Z. The pertinent control clocks the IGBTs such that a pulse-width modulated voltage is applied to the output of the axis module and thus to the motor. The control of the servo inverter generates rotating field that can be sinusoidal, for example. The pulse width is determined by the correcting variable of the current controller. The pulse-width modulated voltage generates a current in the motor that is almost sinusoidal due to the motor and cable inductances.

A diode is connected to each IGBT in inverse parallel. When there is inductive output load, these free-wheeling diodes prevent self-induced voltage occurring in the switching torque from damaging the inverter They conduct the stored energy back to the input of the inverter. Free-wheeling diodes are also used for exchanging reactive energy between the motor and servo inverter.

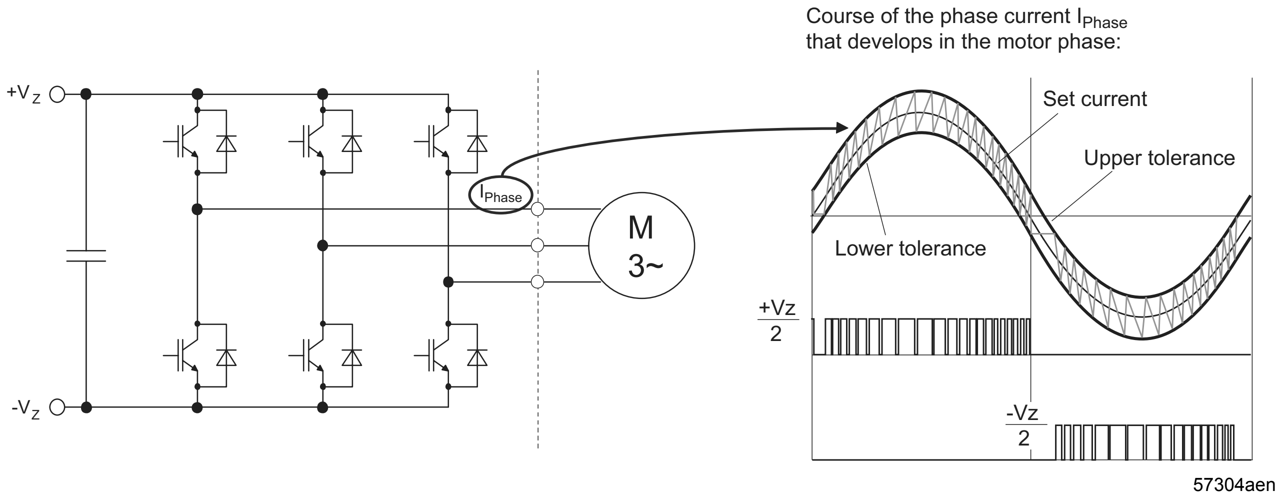

Fig. 66: Block circuit diagram of the inverter, clocked DC link voltage and current flow in motor

4.1.3 Overload monitoring

The overload philosophy of a servo inverter is characterized significantly by the requirements for high dynamic properties – particularly short power peaks. They can last only milliseconds followed by longer "resting phases" that can last for seconds.

A typical overload capacity is between 200 % and 300 % of the rated load for the interval of a second. The mean utilization cannot exceed 100 %.

Due to rapid developments in electronics, especially in the area of processors, there are now sufficient computational resources available in the axis control unit. This allows the unit utilization to be simulated electronically in the unit so it can trigger warning messages or disconnections in a timely manner.

The example diagram in figure 67 depicts the utilization of an axis module starting from a cold state. A loading profile was selected that loads the unit to the utilization limit of 100 %.

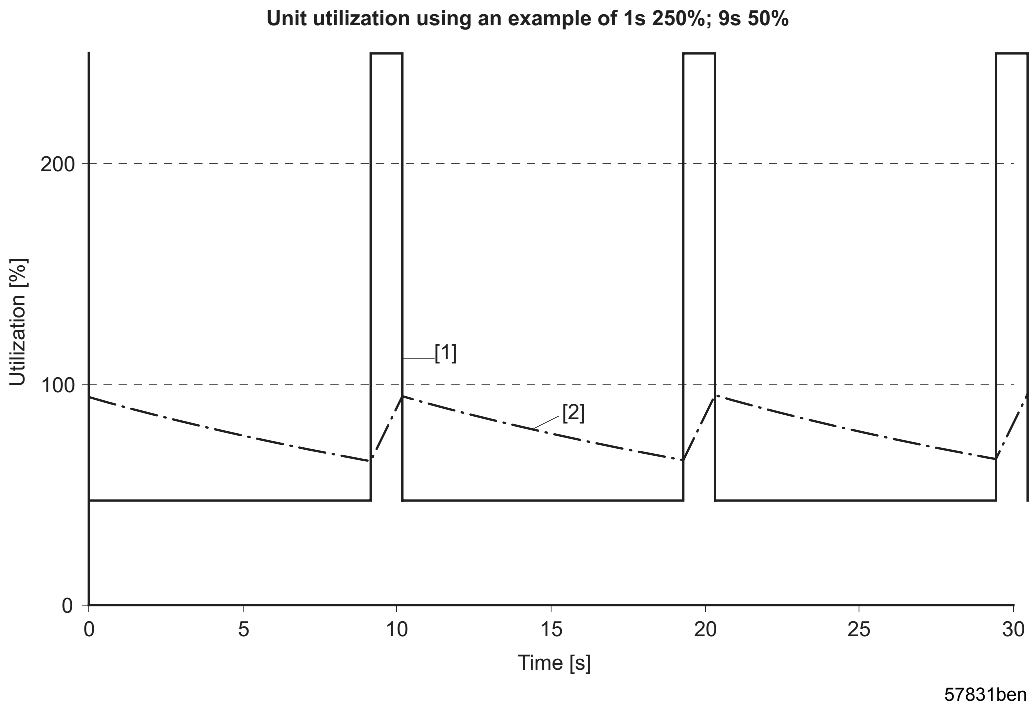

Fig. 67: Example of electromagnetic utilization simulated in a servo inverter

[1] Motor current

[2] Utilization

The curve [1] in the diagram above represents the course of the current that periodically reaches 250 % of the rated current for short periods of time. Using the 100 % line, it is easy to see how the especially the utilization tends to approach the utilization limit at 100 %.

4.1.4 EMC considerations

Modern drive systems are expected to meet an interference immunity class such as EN 61800-3. Whether the system meets the interference immunity class depends strongly on the design and the complying with certain measures.

These include, for example:

- On the power system:
  - Using a line filter between the supply module and the power supply
  - Using short shielded cables between the line filter and the supply module
- On the motor:
  - Using an output choke
  - Using shielded motor cables
  - Complying with maximum motor cable lengths, typically 100 m, as the capacitive earth-leakage currents are otherwise too high
- Installation:
  - Shielding applied to a large area to shield high frequency earth-leakage currents
  - Keep power cables and signals lines apart

For more information, see section 6.5, "Electromagnetic interference and compatibility".

4.1.5 Option cards

Option cards are necessary to make modern servo system scalable. The horizontal and vertical scalability allows you to find cost-effective solutions for almost any application.

Common option cards:

- Fieldbus interfaces such as Profibus, ProfiNet, EtherCAT, and DeviceNet allow the axis connect to a machine control. The control send control commands and setpoints such as the position or velocity to the axis and the axis sends back information about its status as well as process values such as the actual speed or actual position.
- Additional I/O cards are required to process a large number of limit switches or other sensors from the axis. Option cards with analog interfaces also exist that allow the axis to process analog setpoint signals, for example.
- Encoder cards allow the synchronous encoders to be connected, such as for slip-prone tracks or for alternately operating one axis module with multiple motors.

4.2 The modular multi-axis servo system

A modular servo system consist of the following basic components:

- Central supply module
- Axis module(s)

A common supply module supplies multiple axes directly over the DC link. Consequently, only one supply system and one common braking resistor are required for multiple axes. The braking resistor is not required when using a regenerative power supply unit.

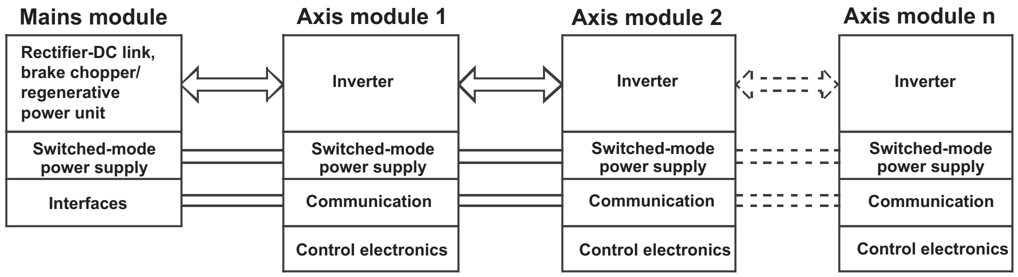

Fig. 68: Basic design of a modular servo inverter system

The advantages of a modularly designed servo system are in the area of multi-axis applications. Depending on the application and operating status, the axes exchange energy over the DC link connection. The energy exchange begins if one or more axes are in motor operation while other are in regenerative operation and can consequently return energy.

A further advantage for multi-axis applications is the reduced installation workload because only one supply system and one braking resistor must be installed in the central supply module.

4.2.1 The supply module

The supply module provides power to the connected axis modules over the DC link. The connection is mostly made directly to the three-phase mains supply. Typical connection values are AC 380 – 500 V, 50 – 60 Hz. A supply module fundamentally consists of the following:

- The rectifier
- The brake chipper and the connecting terminal of the braking resistor[1)] or, alternately, a regenerative power supply unit
- The overvoltage protection
- The connection to a central communication
- A communication bus to the axis modules
- A 24-V connection to the power supply
- Various monitoring functions such as power failure monitoring or measuring the DC link voltage

1) If a braking resistor is used, install and connect it externally. A supply module with an integrated braking resistor can also be used for low incidental energies.

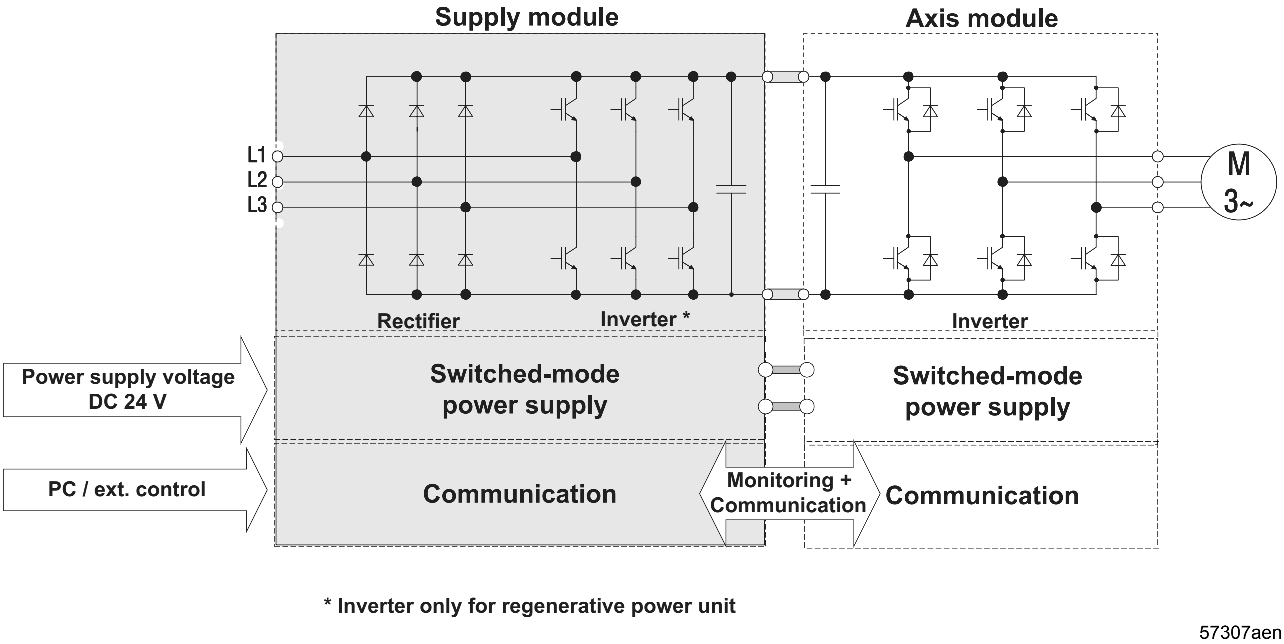

Fig. 69: Basic design of a supply module, display with axis module

In a modular servo inverter system, the DC link is generated in the supply module. It is connected electrically to the axis module via a mechanical DC link connection, such as a rail system.

DC link and energy regeneration

The kinetic energy resulting from the breaking of a drive is converted into electrical energy and is feed back into the DC link. According to the formula below, with a constant DC link capacity, the voltage must rise in order to accept the energy feed into the DC link.

$$E = \frac{1}{2} \times J_{Mot} \times \omega_{Mot}^2 = \frac{1}{2} \times C_{ZK} \times V_{ZK}^2$$

J_{MOT}	Mass moment of inertia of the motor	C_{ZK}	Capacity of the DC link, constant
ω_{MOT}	Angular velocity of the motor	V_{ZK}	DC link voltage

If the drive is now braked, the spare energy must be dissipated.

Basically, there are four ways to do this:

- Regenerative power unit, that is the energy can be used by other consumers
- The brake chopper and braking resistor convert the energy into heat energy
- Energy exchange with multi-axis applications by using the electrical energy of other connected motors
- Capacity module (capacitor module) to increase the DC link capacity

4.2.2 Regenerative power unit

The regenerative power unit has the advantage that braking energy is available as electrical energy for other users in the power supply.

There are various ways of implement a regenerative power unit, such as with inverse parallel bridges. With this form of regenerative power unit, the supply system rectifier is supplemented with an inverter that is controlled synchronously with the supply system. If the DC link voltage exceeds the rectifier value, the spare energy is feed back into the power supply.

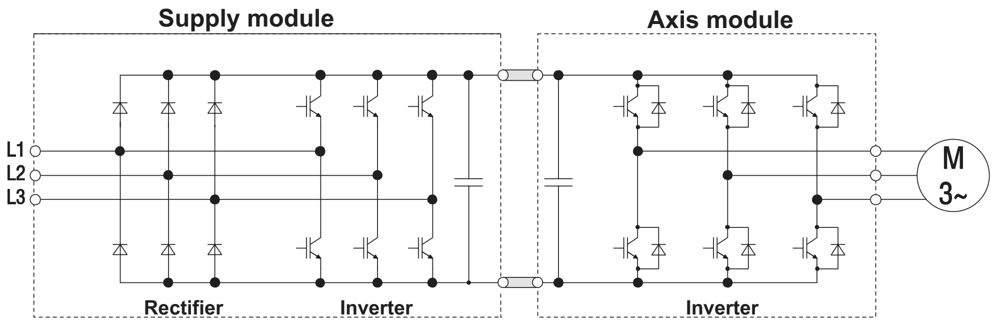

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Fig. 70: Basic design of a supply module with regenerative power unit

4.2.3 Brake chopper and braking resistor

In contrast to the regenerative power unit, with the brake chopper, the spare energy is not fed back into the power supply, but is instead converted into heat with a braking resistor. If only little braking work is to be performed, the design with the brake chopper and the associated braking resistor is the more cost-effective alternative when compared to the regenerative power unit.

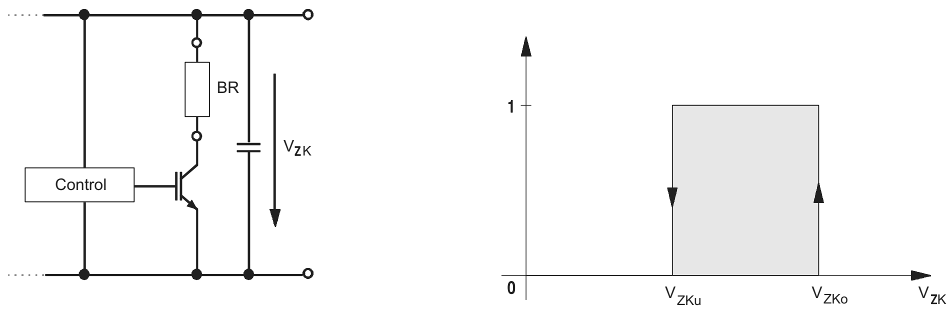

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Fig. 71: Controlling the brake chopper, brake chopper switching behavior

V_{ZKu}	Lower DC link voltage limit
V_{ZKo}	Upper DC link voltage limit

4.2.4 Regenerative power unit and brake chopper comparison

Depending on the application, the process that is best suited must be choosing during project planning.

	Regenerative power unit	Brake chopper and braking resistor
Criterion		
Position	Completely integrated in supply module.	Brake chopper in supply module. Braking resistor outside of the control cabinet.
Effect on ambient temperature	Very low.	Heat buildup around braking resistor
Additional wiring	–	Braking resistor connection.
Energy balance	Electrical energy retained.	Electrical energy is converted into heat energy.
Costs	The regenerative power unit is more expensive than the braking resistor.	The braking resistor is relatively inexpensive.
EMC	Possible power supply disturbance to other consumers.	Lower power supply disturbance than with regenerative power unit.

4.2.5 The axis module

The axis module controls a servomotor with a variable-frequency, three-phase rotating field.

An axis module fundamentally consists of the following:

- An inverter-IGBT bridge as a power output stage
- Communication interface and binary inputs and outputs as basic functions of control technology
- Motor-encoder interfaces
- Slots for options such as encoders, fieldbuses, additional binary inputs and outputs
- Slots for control cards
- A control for the motor brake
- An evaluation of the motor temperature sensor
- Equipment to implement the "Safe Stop" safety technology in accordance with EN 60204-1.
- A display for showing the operating status
- Internal operation monitoring functions.

The IGBTs have become accepted as robust power transistors for this applications.

The main advantages of IGBTs:

- Low switching losses
- Simple control
- High switching frequencies
- High dielectric strength

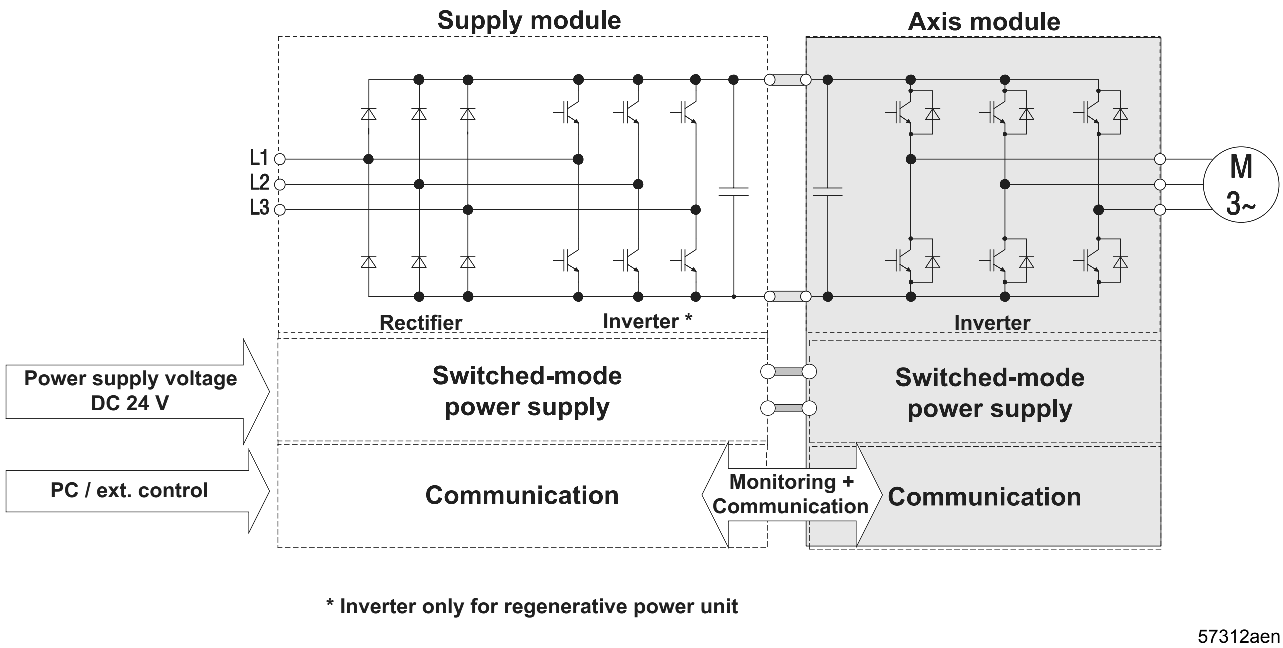

Fig. 72: Basic design of an axis module, display with supply module

The number of axes that can be connected to the supply module is limited.

The limit is set by:

- The power the of supply module
- The total or peak power of the axis module
- The maximum number of addressable axes
- The mechanical design
- The selection of the DC link connection

4.2.6 24 V supply

Supplies that do not depend on the three-phase mains supply have become common for supplying voltage to the control section of servo inverters. The units have a DC 24-V connection, separate from the power supply.

To supply industrial low-voltage consumers such as PLC and control sections of servo inverters, the 24-V voltage supply is used in accordance with EN 61131. In some cases, a voltage with a tight tolerance is required, such as for brake voltage. In these cases, conventional power supply technology with a B4 diode bridge is no longer sufficient and a switched-mode power supply is used.

Voltage supplies that do not depend on the DC link generally have the advantage that the units can still be configured and can still function even if the supply system is switched off. This can be important if the units are installed in a fieldbus system, for example. If the units are independently supplied with 24 V, this is called backup mode, which makes it possible to operate the bus system without a power supply connection.

As depicted in figure 73, it is sufficient to make the 24-V supply available externally for modular systems, and to then pass it from unit to unit.

The 24-V supply for the motor break control and the electronics are implemented separately. To ensure safe operation, the two voltages in the units are monitored for required tolerances.

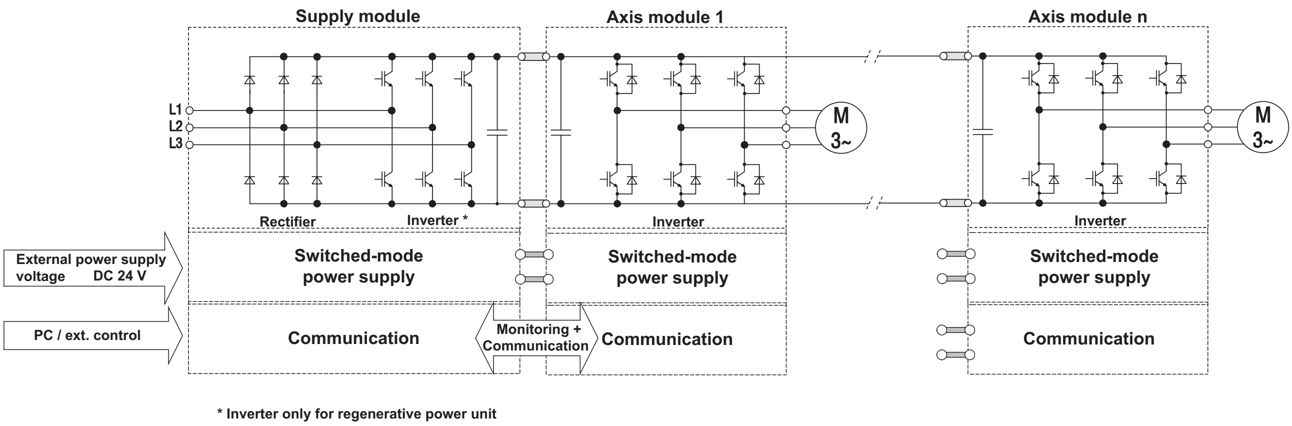

Fig. 73: Basic design of an modular multi-axis system with external 24-V supply

4.3 The single-axis inverter

Single-axis inverters, also called compact inverters, have the advantage of being available as a complete unit. In their housing, they contain the DC link with brake chopper, inverter, rectifier, switched-mode power supply, option slots, communication interfaces and CPU component(s) for communication and control functions. Consequently, it is not necessary to connect the individual unit components as with a modular system.

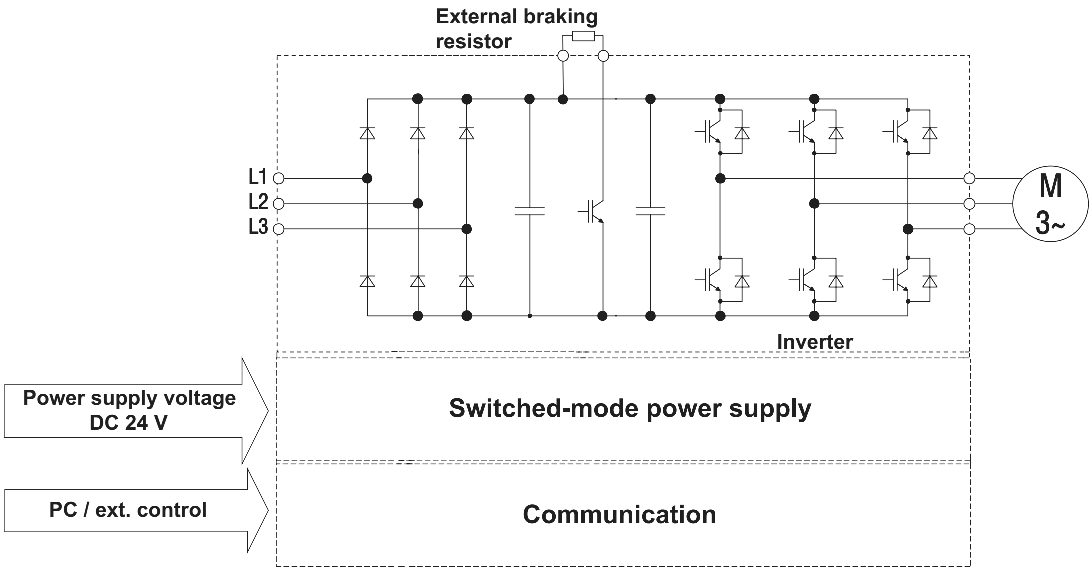

Fig. 74: Basic design of a single-axis inverter

The functions of the power section (the mains module and the inverter) correspond to the functions of the servo inverter systems described in section 4.2.

4.4 Modular multi-axis system/single-axis system comparison

The following advantages of both systems help you decide whether an application is best served by a modular multi-axis system or with a single-axis system.

Advantages of the modular multi-axis system

- Only power supply input, meaning less installation workload
- Only a braking resister, as long as there is no regenerative power unit, meaning lower installation workload
- Less spaced required in control cabinet with approx. 3 or more axes (compared to single-axis units) due to the reduced installation workload
- Power exchange between axis modules via DC link connection
- Simple information exchange between individual axis modules over common system and signaling bus.

Advantages of the single-axis system

- Decentralized position possible to avoid large motor cable lengths
- For application with up to approx. two or three axes, the single-axis inverter is usually the less expensive solution
- For low power and low numbers of axes, the single-axis inverter is usually the less expensive solution

4.5 Definitions

Term/abbreviation	Definition/explanation
IGBT	**I**nsulated **G**ate **B**ipolar **T**ransistor, power semiconductors
EMC	**E**lectro**m**agnetic **c**ompatibility
I/O cards	**I**nput/**O**utput cards
PLC	**P**rogrammable **L**ogic **C**ontroller
CPU	**C**entral **P**rocessing **U**nit, main processor

5 Control Design and Operating Modes

This section deals with control design with sinusoidal supply. For more information on this and on block-shaped supply, see section 2.4, "Theory of operation of synchronous servomotors".

5.1 Overview

Servo drives are used for many applications for position or speed control. The control system is usually designed in a cascading formation such that the control systems overlay each other.

- The innermost control system controls the current. Only this controller can control torque.
- Overlaying the current controller with a closed-loop speed controller allows you to control the speed.
- In addition, overlaying the current controller with a position controller allows you to control the position.

Figure 75 displays the basic structure of the control design of a servo controller. The controllers of today's servo inverters are usually fully digital.

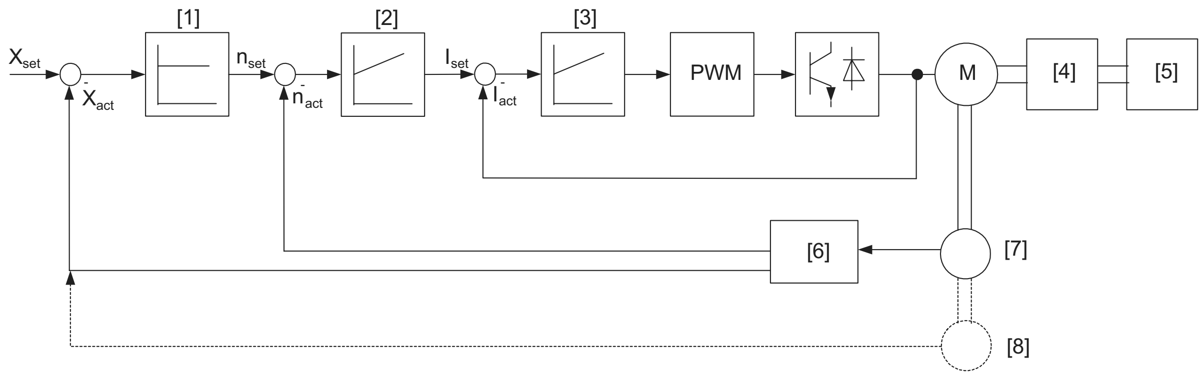

Fig. 75: Basic design of the control design of a servo controller

[1]	Position controller Kp_x	[5]	Load
[2]	Speed controller Kp_n	[6]	Signal processing
[3]	Current controller	[7]	Encoder
[4]	Gear unit (optional)	[8]	Absolute value encoder

The individual controller types are explained in detail in the following sections.

5.2 Current control

The motion action of a servo drive is determined directly by the torque of the motor. The torque itself is determined by the currents in the motor. To implement a torque setpoint as dynamically as possible at the motor shaft, it is necessary to not only apply a controlled voltage to the motor (V/f mode) but also to control the currents.

Controllable AC motors (synchronous and asynchronous motors) are operated with three-phase alternating current. The three currents (U, V, W) however, are not independent of each other. The total of the three currents must always equal zero. This means that one current component can always be calculated with the other two. For example, you can find the current in phase W with the currents in phases U and V. Two controllers that are independent of each other are sufficient to control the motor currents. If, for example, the currents of phases U and V are controlled, the current in phase W is fixed.

The direct control of the phase currents has a disadvantage, however. If the motor speed increases, sinusoidal currents with increasing frequency must be controlled. This leads to a phase shift between the current setpoints and current actual values, as due to their operating principle, controllers can only correct setpoint changes so fast. The delay of the actual value with respect to the set value of the controller is to be taken as constant, and thus the phase shift between the set current and actual current increases the higher the speed is.

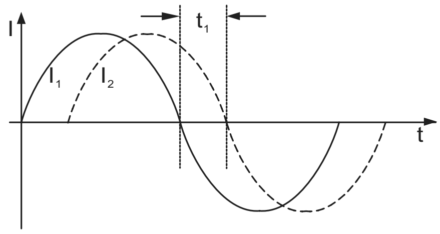

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Fig. 76: Difference of the set and actual current amplitudes

I_1	Set current
I_2	Actual current
t_1	Controller delay

There is a difference between the setpoints and actual values even in steady-state condition, with no change to the current amplitude. The computing capacity of today's processors allows the actual currents to be changed into a system of identical magnitudes with a coordinate transformation. These identical magnitudes are then controlled. Subsequently, the motor voltages are transformed back as correcting variables of the controller.

The component I_{sq} that produces the torque and the component I_{sd} that produces the magnetic field are used as set values for the current controller. For more information, we recommend literature on the subject of "field-oriented control of AC motors".

The correcting variable of the current controller is the motor voltage. The motor voltage is specified by a pulse-width modulation in time-discrete form. The voltage between two phases of the servo inverter output can only accept three voltage potentials here.

The desired fundamental wave of the voltage is obtained by switching quickly between $+V_Z$ and $-V_Z$. Common frequencies for pulse-width modulation are 4 kHz, 8 kHz, 16 kHz.

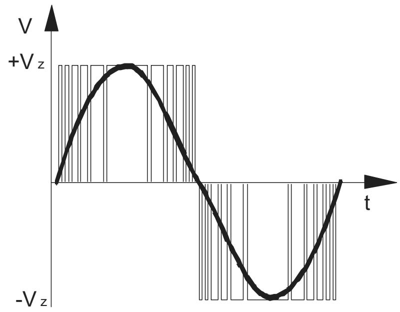

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Fig. 77: Pulse-width modulation (PWM)

As a voltage change can only take place in the PWM interval, current controllers usually work with the frequency of the PWM as well. Intelligent digital current control processes now allow a current setpoint change to be corrected in virtually one sampling step. For example, a high current control frequency of 8 kHz means a current correction time of 125 µs.

The parameters of the closed-loop control system are important for the parameters settings of the current controller. These are set only by the motor connected to the servo inverter. In servo inverters from SEW-EURODRIVE, the current controller is therefore configured optimally when the motor is started up.

5.3 *Speed control*

5.3.1 Speed control structure

This illustration shows the basic structure of speed control.

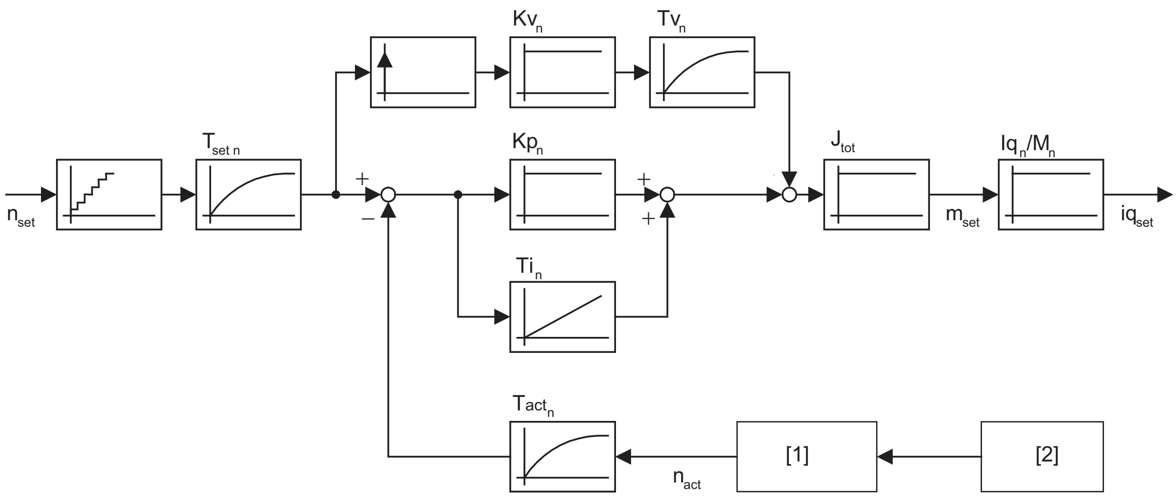

Fig. 78: Speed control structure

[1]	Speed calculation	Ti_n	Adjustment time
[2]	Motor encoder	$T_{act\ n}$	Speed adjustment filter
n_{set}	Setpoint speed	Tv_n	Acceleration feedforward filter
n_{act}	Actual speed	J_{tot}	Total mass inertia
$T_{set\ n}$	Time constant of the speed controller	Iq_n/M_n	Motor constant
Kv_n	Amplification acceleration feedforward	m_{set}	Setpoint torque
Kp_n	Position controller	iq_{set}	Setpoint of torque-producing current

The difference of the signals is given to a PI controller after processing the following:

- The speed setpoint, see page 85,
- The detection of the actual speed value, see page 83
- The actual speed value, see page 85

The correcting variable of the PI controller is responsible for the acceleration of the drive. The required torque can be calculated from the inertia of the driveline.

The torque-producing current that is supplied to the current controller can be calculated from the reciprocal value of the motor constant $k_T = M_n/I_{qn}$.

An acceleration feedforward has been implemented to improve the dynamic properties of the control response; see page 87.

5.3.2 Position and speed detection

Various encoder systems are used to detect position and speed. The encoders can be distinguished by the following criteria:

- Encoders with absolute information about the position, such as resolvers, HIPERFACE (encoder system from Sick/Stegmann), and EnDat (encoder system from Heidenhain)
- Encoders with purely incremental information about the position such as TTL encoders and sin/code encoders

Permanent-field synchronous motors require absolute position information for motor control. For this reason, absolute value encoders are usually used for this motor type.

It is also appropriate to use an absolute value encoder if the position should be detected without referencing right after the drive is switched on. The resolver is not as well suited for this type of use as it can only provide the absolute position information within one motor revolution.

Both encoders with absolute information and encoders with purely incremental information only provide information about the position. From this information, the servo inverter determines the speed by sampling the position at regular intervals. The speed is calculated from the difference in position from two sampled position values over the known difference in time. In this way you can see that the speed is not available as an instantaneous value at a certain point in time, but rather as an mean value over a sampling interval.

Speed control requires high dynamic properties and an actual speed value that is as current as possible. For this reason, a short sampling interval must be chosen. The resolution of the encoder system plays a decisive role. The aforementioned encoder systems offer the following resolutions per motor revolution:

- Resolver: With the newest evaluation processes, the resolver signal can be evaluation with 15 bits, resulting in a resolution of 2^{15} = 32768 increments/revolution.
- TTL encoders: With a resolution of 1024 impulses/revolution, resulting in a resolution of 4 × encoder resolution because both of the encoder tracks that are shifted by 90° in the servo inverter. In other words, 4 x 1024 = 4096 increments/revolution. Consequently, it is perfectly sufficient to evaluate with 12 bits in the servo inverter (2^{12} = 4096).

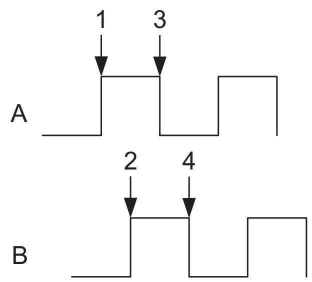

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Fig. 79: TTL encoder signals

- sin/cos encoders, HIPERFACE, EnDat: The resolution is 2^{10} × encoder resolution. The servo inverter evaluates with 2^{10} × 1024 = 1048576.

Due to the position resolutions of the various encoders, depicting the speed over a time interval of 500 µs, for example, results in the following resolutions for the speed:

Resolvers

$$\frac{1\ \text{revolution}}{2^{15}} = 3.05175 \times 10^{-5}\ \text{revolutions}$$

$$\frac{3.05175 \times 10^{-5}\ \text{revolutions}}{500\ \mu s} = 0.061\ \frac{1}{s} = 3.66\ \frac{1}{\text{min}}$$

TTL encoders (1024 graduations)

$$\frac{1\ \text{revolution}}{4096} = 2.44 \times 10^{-4}\ \text{revolutions}$$

$$\frac{2.44 \times 10^{-4}\ \text{revolutions}}{500\ \mu s} = 0.48828\ \frac{1}{s} = 29.3\ \frac{1}{\text{min}}$$

sin/cos encoders

$$\frac{1\ \text{revolutions}}{1024 \times 2^{10}} = 9.5367 \times 10^{-7}\ \text{revolutions}$$

$$\frac{9.5367 \times 10^{-7}\ \text{revolutions}}{500\ \mu s} = 1.907348 \times 10^{-3}\ \frac{1}{s} = 0.114\ \frac{1}{\text{min}}$$

The differences in the quantization of the speed value in the various encoder systems are obvious. The quantization results in a "speed ripple". The following graph displays the resulting ripple with a common TTL encoder with a resolution of 1024 graduations together with a speed controller sampling time of 500 µs.

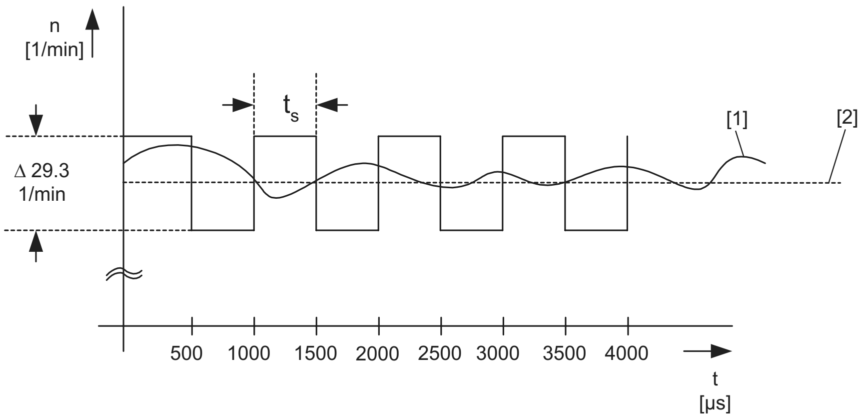

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Fig. 80: Display of the speed ripple

t_s	Sampling interval n-controller
[1]	Actual speed
[2]	Set speed

This "ripple" of the actual speed value is transferred to the torque setpoint via the speed controller. Values can occur here that are so large that they can no longer be tolerated. A ripple of 10 % of the rated motor torque generally cannot be exceeded.

5.3.3 Actual speed value filter

As explained in the previous section, the ripple of the motor torque must be limited. As the ripple stems from the actual speed value, it is necessary to filter this value accordingly. For this, the required time constant depends on the following factors:

- Encoder type used
- Gain of the speed controller
- Mass inertia

Filters have an undesirable effect; they delay the actual speed value. This delay then limits the dynamic properties of the speed control system.

For this reason, only as much as strictly needed should be filtered. Several values interact with each other here:

- Resolution of the encoder system
- Maximum torque ripple
- Desired dynamic properties in the speed control system
- Mass inertia
- Filter time constant of the actual speed value filter

Obviously, it can be difficult to take all these relationships into account and to correctly set all parameters of the control system. Modern startup tools can provide valuable assistance by automatically processing these relationships; for more, see "Stiffness" on page 89.

5.3.4 Processing the speed setpoint

It may be necessary to process the externally supplied speed setpoint before it is passed to the controller, such as if the setpoint is in analog form or if filtering is needed. This filtering reduces the resulting torque ripple, as with the actual speed value.

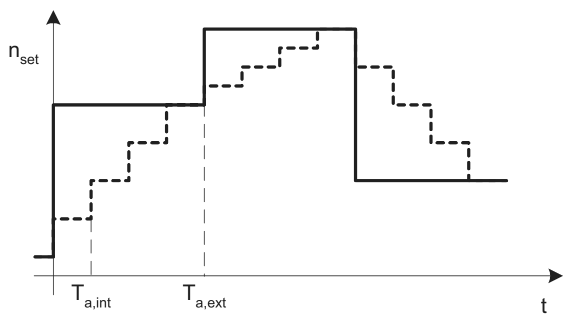

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Fig. 81: Fine interpolator

$T_{a,int}$	Sampling time of the speed controller
$T_{a,ext}$	Sampling time of the external setpoint source

The setpoint is usually in digital form, however. If the setpoint source works slower than the internal controller, it may be appropriate to direct the setpoint through a "fine interpolator". The fine interpolator reduces the rough quantization of the signal. This also reduces the torque ripple.

Figure 81 illustrates the situation described above.

The solid line represents the input and the dotted line represents the output of the fine interpolator.

5.3.5 Speed controller

Using permitted approximations, which will not be explained here further, the transmission behavior of the speed control can be described as a first-order filter.

For this, the time constant describes the dynamic properties of the control system and is calculated as follows:

$$T_n = \frac{1}{Kp_n}$$

T_n Time constant of the speed controller
Kp_n P component of the speed controller

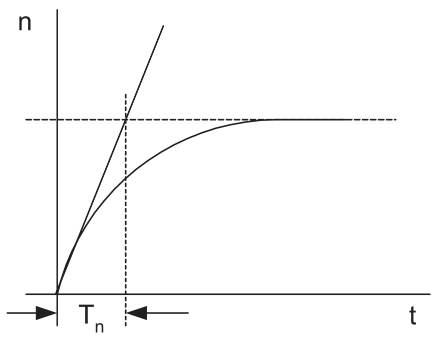

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Fig. 82: Step response mode of P_{t1} element

There is a minimum time constant with which the control system can still work stably. If the time constant falls blow this limit due to an increase of , the speed control system begins to vibrate. The following factors determine smallest attainable value T_n:

- Dynamic properties of the current controller
- Time characteristic of actual speed value detection (sampling interval for position detection)
- Calculation time of the digital speed controller
- Sampling frequency of the speed controller

The integrator (I component) of the speed controller does not have any substantial influence on the time constant T_n. Its task is to avoid remaining system deviations between the speed setpoint and the actual speed value for any load torques. The set integrator parameters influence the transient response of the actual speed value. Normally, "aperiodic transient response" is set there.

Both of the next sections show that the mass inertia has a substantial influence on the dynamic properties of the speed controller.

5.3.6 Acceleration feedforward

The acceleration feedforward causes an increase in the dynamic properties of the control system's control response. This increase in dynamic properties is independent of the control system's time constant.

Note that the acceleration feedforward does not influence the dynamic properties of the disturbance correction such as step changes in load. These are only determined by the time constant of the speed control system.

For the acceleration feedforward, an acceleration value is determined from the change of the speed setpoint over time that is added to the correcting variable of the speed controller. In this way, a torque can arise at the motor shaft at a point in time even before the controller detects a difference between the speed setpoint and the actual speed value.

If the speed setpoint is full of high frequency interference (if it is "noisy"), it must be filtered to keep the torque ripple small. Here too, filtering delays the acceleration signal, reducing the dynamic properties of the control response. The feedforward value can also be scaled. However, this parameter is usually set to 100 %.

5.3.7 Load coupling without backlash

A mass can be coupled to a servomotor with or without backlash. This section contains information on load coupling without backlash.

Load coupling without backlash means that the load directly follows every movement of the motor, even the smallest load change. These kinds of drives are often called direct drives.

Coupling a mass increases the mass moment of inertia J_{tot} compared to the idle motor. If the torque ripple remains within the permitted range in spite of the higher inertia, a drive with a coupled load without backlash can also be operated with the same dynamic properties as an idle motor.

However, if the mass inertia J_{tot} increases so much that the torque ripple leaves the permitted range, the time constant of the filter must be raised for the actual speed value. As described above, the actual value filter limits the dynamic properties of the controller. Because of this, it is required to increase the time constant of the control system by reducing Kp_n. Here it is clear that encoder systems with high resolutions that keep the torque ripple small without a high actual value filter offer advantages for the dynamic properties of the control system.

$$J_{tot} = J_{Mot} + J_{ext}$$

J_{tot} Total mass inertia

J_{Mot} Mass inertia of the motor

J_{ext} Mass inertia of the load, reduced on motor shaft

5.3.8 Load coupling with backlash

Load coupling with backlash means that the load does not directly follow every movement of the motor, such as a speed-controlled motor moving without the load moving with it. This is typically the case when mounting a gear unit to a motor.

If the speed controller is set with the minimum possible time constant and the parameter J_{tot} is set to the total mass inertia $J_{Mot} + J_{ext}$, this will only work as long as the motor and load move together.

If the motor moves within the backlash, the speed controller sets torques that are too high, as it does not notice that the load is "missing". Due to the torques that are too high, the time constant of the control system falls below the minimum time constant and the controller becomes instable. To prevent this, the gain Kp_n of the controller must be reduced by the factor $J_{Mot} / (J_{Mot} + J_{ext})$. This produces the minimum time constant for the speed controller for load coupling with backlash.

$$T_{n,Back} = T_{n,Motor} \times \frac{J_{Mot} + J_{ext}}{J_{Mot}}$$

$T_{n,\ Back}$	Time constant of the entire drive
$T_{n,\ Motor}$	Time constant of idle motor
J_{ext}	Mass inertia of the load, reduced on motor shaft
J_{Mot}	Mass inertia of the motor

A drive with backlash is thus slower than the minimum possible time constant of the speed controller by the mass inertia ratio according to the section "Stiffness"; for more, see page 89. For example, if a load is coupled with a 100-fold motor mass inertia, and if the speed controller has a minimally attainable time constant T_n of 2 ms, then the minimal possible time constant for this drive is 202 ms.

5.4 Position control

The position controller is generally implemented as a P controller. The integrator in the subordinate speed control system guarantees that no system deviations remain, even for interference in the form of load torque.

If you consider the transmission behavior of the subordinate speed controller as per the "Speed control" section on page 86 with a first-order filter, then a second-order system will result for the position controller. In most applications, it is required that the transient response of the actual position value does not overshoot, that is "critical damping" without moving beyond the target position. This is possible with the highest possible dynamic properties from setting the parameters of the P position controller as follows:

$$Kp_x = \frac{Kp_n}{2}$$

Kp_x P component of the position controller

Kp_n P component of the speed controller

Stiffness

The previous sections have shown that there is a wide range of relationships for setting the parameters of the position and speed control systems. To make the startup process easier, SEW-EURODRIVE has added the "Stiffness" value. This value is used to select desired dynamic properties of the driveline. During startup, you can use this value to successively approach the stability limit of the control system. In this way you are guaranteed that the peripheral conditions are met such as the lowest possible actual speed value filter while meeting the maximum permitted torque ripple for a given position resolution of the encoder.

5.5 Definitions

Term/abbreviation	Definition/explanation
HIPERFACE® (Hiperface)	**Hi**gh **Per**formance Inter**face**. Registered trademark of the company Sick Stegmann GmbH.
Integrator	Creates a correcting variable that increases as long as there is a deviation
Kp	Proportional gain of the controller
Kv	Scaling factor of the feedforward
P element	Proportional gain
PWM	**P**ulse-**w**idth **m**odulation
Control system	Consists of: setpoint/actual value comparison, controller, closed-loop control system
Ripple/noise/cogging	Oscillations of a value around its mean value
Ti_n	Reset time of the integrator
Time constant/dynamic properties of a control system	Response speed of a control system
Delay	Delay time of a control system until a change occurs
V/f mode	Voltage/frequency control mode

6 Industrial Use

6.1 Supply system conditions

Today's industrial power supply systems operate with a sinusoidal voltage and a rated frequency between 50 and 60 Hz. Servo inverters can be operated in the majority of system configurations such as TN and TT power systems.

Voltage fluctuations in the power supply influence the operating characteristics of the drive. The inverter switches off if the rated voltage range is exceed to avoid damage. If the voltage falls below the rated voltage range, the motor can no longer supply the nominal values specified in the technical data.

Line chokes and built-in overvoltage protection make servo inverters less sensitive to voltage peaks that make their way into the power supply from other consumers or compensation equipment that lack chokes.

6.2 Environmental conditions

Pay particular attention to the environmental conditions that are defined as permitted during project planning.

Important environmental conditions:

- Altitude Modern servo inverters are usually rated so that they can operated at an altitude of 1000 m with no limitations. If the units are operated at higher altitudes, keep in mind that they will be derated (their power reduced). Lower heat dissipation due to the lower air pressure and lower flashover resistance in this environment cause this reduction in power.
- Ambient temperature Temperatures between approx. 0 °C and 45 °C are common. Higher temperatures derate the units due to reduced heat dissipation.
- Storage temperature Generally, a larger range of temperatures is permitted for storage than for operation, as the unit does not produce any heat to be dissipated. However, ensure that the temperature does not fall below the lowest permitted temperature, as the capacitors could totally discharge. After longer storage and after a total discharge, the capacitors must be formed to the supply voltage before the unit is connected.
- Pollution class according to IEC 60664-1; VDE 0110-1.
- Interference immunity.

6.3 Notes on the motor

Servo inverters work with vector-oriented control modes. Exact data from the connected motor is required to make such modes possible and to obtain optimal controller results. For this reason, manufacturers are generally only allowed to connect motors to servo inverters and to operate those whose data is known to the servo inverter or startup tool. Non-SEW motors must be measured before operation to be able to adjust the controller with exact data.

Additionally, motors and servo inverters must be tuned to each other with regards to power during project planning. Ensure that the servo inverter can provide the required currents for the peak torques; see also section 8, "Project Planning".

6.3.1 Synchronous motors

Synchronous permanent-field servomotors not usually ventilated. As the heat is dissipated via convection, the coating and the contamination of the motor are very important. The protection type of these motors is usually IP65, but this must be checked using the motor data sheet during project planning.

The thermal limit torque can be optionally increased using a forced cooling fan in many cases. The motor characteristic curve provide additional information.

6.3.2 Asynchronous motors

Asynchronous servomotors are usually fan cooled which is why special attention should be paid to the thermal loading for continuous loads in the lower speed range. The operating point (the effective torque at medium speed) must lie below or maximally on the thermal limit characteristic curve. Due to the reduced cooling capacity at lower speeds, the characteristic curve exhibits lower values as well in this range; see also section 2.6.1, "Motor characteristic curve".

6.4 Cable installation

The cable quality and installation plays a large role in the use of servo drives. The dimensioning must be geared towards the flowing current in order to limit the voltage drop to the permitted value. For further dimensioning criteria, see the applicable regulations.

Cable installation requires the utmost care, especially in cable ducts or racks. Keeping power cables and electronic cables separate reduces electromagnetic interference. Shielded cables are also well suited to reduce electromagnetic interferences in the system. For additional information, see the regulations of the system, country, or manufacturer.

6.5 Electromagnetic interference and compatibility

This section will explain the most important terms on the topic "Electromagnetic compatibility".

Additional documentation

For more information, please refer to the SEW-EURODRIVE publication "Drive Engineering – Practical Implementation, Electromagnetic Compatibility (EMC) in Drive Engineering".

The following topics are discussed there in detail:

- Interference factor
- EMC planning
- EMC measures
- Standards and regulations
- EMC terms
- Working principle of EMC components such as line filters and chokes

Terminology

Electromagnetic interference is defined in the respective laws as any electromagnetic phenomenon that may degrade the performance of a unit. Causes of electromagnetic interference can include:

- ESD = Electrostatic discharge
- Surge = Voltage pulse such as effects of a thunderstorm or switching operations in the supply system
- Conducted and radiated HF coupling
- Burst = Fast transients due to opening contacts in inductive circuits

In the area of electromagnetic interference, the following terms are distinguished:

- Interference immunity: The ability of a unit to perform without functional problems in the presence of an electromagnetic disturbance (EMI = electromagnetic interference, immission behavior). The interference immunity is a quality characteristic of the interference sink.
- Emitted interference: The ability of a unit to generate electromagnetic signals that can cause functional problems in other units (EME = electromagnetic emission, emission behavior). Emitted interference is a quality characteristic of the interference source.

Standards and guidelines

Servo inverters and accessories are components that are intended for installation in machines and systems and must therefore meet the EMC product standard EN 61800-3 "Variable-Speed Electrical Drives". System- and country-specific regulations must also be observed.

The electromagnetic compatibility of the components of a system and of the complete system is very important. EMC directives define the permitted ratios.

The following standards are used:

<table>
<tr><td colspan="2" align="center">EMC product standard for speed-dependent drive systems

EN 61800-3</td></tr>
<tr><td align="center">Emitted interference

EN 550xx</td><td align="center">Interference immunity

EN 61000-4 .. x</td></tr>
</table>

There are two kinds of emitted interference:

- Limit value class A (EN 55011): The unit is intended for use in residential areas, provided that system project planning and installation are carried out by electricians (basis knowledge of measures for complying with EMC can be assumed). Encountered often in industrial areas, as higher interference levels are allowed there.
- Limit value class B (EN 55011): Usually, lower interference levels must be met in residential areas in order to avoid interfering with broadcast receivers.

It is important to know which limits must be met and which measures are required to do so during project planning for a servo application. A servo inverter alone cannot guarantee the observance or a limit value class. This is determined primarily by:

- Any necessary additional components such as line filters, chokes, and motor cables
- An EMC-compliant installation

Implementing the EMC measures

The unit manufacturer is responsible for making concrete suggestions for how to carry out the EMC-compliant installation of its servo inverter. However, the system manufacturer or operator is responsible for performing the installation. This section can only give general tips, and in no way replaces the manufacturer-, system-, or country-specific or legal regulations.

Servo inverters are partially equipped with a line filter at the factory and thus the emitted interference from the power supply is already reduced without the user having to carry out any additional measures. Shielded motor cables or output chokes are often used to ensure that the motor complies with limit value classes. As the measures required to comply with EMC limit value classes can be very different from unit to unit, refer to the respective product documentation.

Once again, please refer to the SEW-EURODRIVE publication "Drive Engineering – Practical Implementation, Electromagnetic Compatibility (EMC) in Drive Engineering" for information on EMC.

6.6 Unit interfaces

A large number of unit interfaces allows for various networking options. The following sections provide an overview of the most important and most often encountered networking options of industrial unit interfaces.

6.6.1 Fieldbus systems: Connection to the machine control

Fieldbus systems can digitally link industrial automation engineering components.

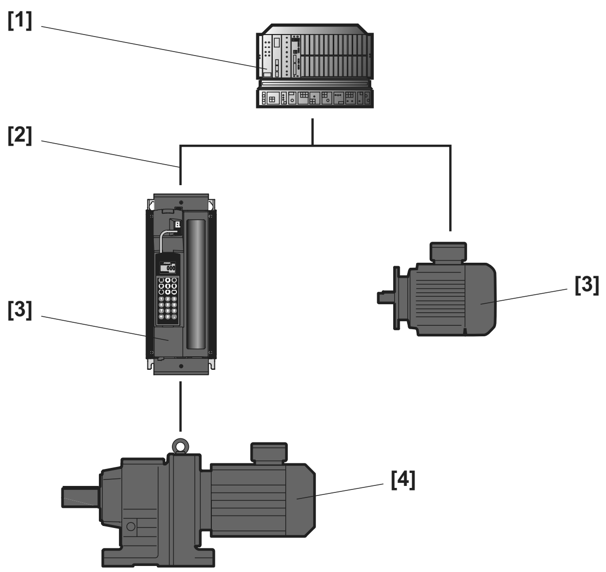

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Fig. 83: PLC control with fieldbus master and slave

[1] Fieldbus master (control)
[2] Fieldbus
[3] Fieldbus slaves
[4] Geared motor

The fieldbus master coordinates the data transfer on the fieldbus. Usually, a **p**rogrammable **l**ogic **c**ontroller (PLC) or industry PC is used. Drive systems, intelligent sensors, and actuators are used for lower-level slaves.

Cyclical data transfer

Data transfer can contain both cyclic and acyclic data. Cyclic data is data that is time critical and must be processed and transferred quickly. The process data consists of process output data and process input data. Process output data contains setpoints that are sent from the master to a slave. Process input data contains actual values that are sent back to the master from a slave.

Acyclical data transfer

In addition to process data, most fieldbus systems provide a parameter channel that usually works acyclically and thus either does not influence cyclic data transfer or only does so minimally. Using read and write services, the master can access unit information in addition to the defined setpoints and actual values.

This often involves:

- Reading individual unit information such as fault memory
- Reading and writing entire data sets such as parameter sets, measuring traces, and cam curve points

Common fieldbus systems:

- PROFIBUS DP
- DeviceNet
- INTERBUS-S

As an example, features of the PROFIBUS DP and INTERBUS-S bus systems are listed in the following sections.

6.6.2 Profibus DP fieldbus system

Features

- Profibus stands for "**Pro**cess **Fi**eld **Bus**" and was developed by SIEMENS AG.
- International market leaders from the automation engineering industry have come together to form the PROFIBUS user organization. Together with the members, they encourage international acceptance of PROFIBUS. The main tasks of the organization:
  - Joint marketing activities
  - Distribution of information
  - Ongoing technological development
  - Allocation and management of PROFIBUS identity numbers
- Usually, the "PROFIBUS DP" ("**D**ecentralized **P**eriphery") protocol is used:
  - Protocol extension "DP-V1" (Version 1: acyclic parameter services)
  - Protocol extension "DP-V2" (Version 2: cycle synchronization)
- Line topology based on RS485:
  - 12 mbit/s up to 100 m cable length
  - 9.6 kbit/s up to 1.5 km cable length

- Transmission medium is usually copper, fiber-optic cable is very rare
- Up to 126 stations possible, however such a number will cause lower performance accordingly. Access via polling.
- The master requires a GSD (**G**eräte**s**tamm**d**atei = unit master file) from each slave (of type station)

Example

The following figure is of a Profibus design with bus stations placed centrally in the control cabinet, here MOVIDRIVE® servo inverters from SEW-EURODRIVE, and remotely arranged bus stations, here MOVIMOT® from SEW-EURODRIVE.

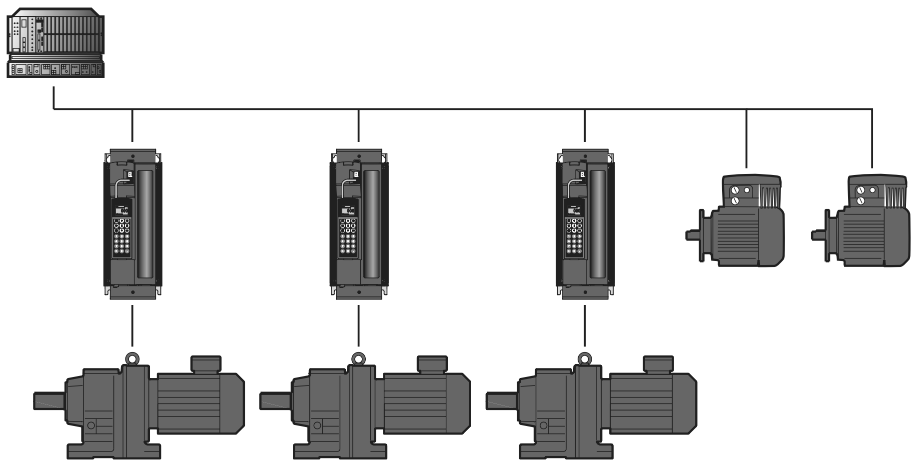

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Fig. 84: Example of a Profibus topology

6.6.3 INTERBUS-S fieldbus system

Features

- INTERBUS-S was developed by Phoenix Contact GmbH & Co.
- The INTERBUS-Club e.V. is an international organization of companies with the common goal of advancing INTERBUS technology as well as automation solutions with INTERBUS and complementary technologies.
- Ring topology based on RS485:
  - Each station can act as an inverter/repeater
- Up to 2 mbit/s data transmission rate
- Very short cycle time due to high level of data efficiency
- Total frame protocol: Instead of sending individual messages to every station, the master sends a total message in which the individual messages are strung together and sent to every station. This reduces the cycle time considerably.
- Data is pushed onto a register, see figure 85
- Easy to convert to fiber-optic technology
- Simple troubleshooting
- Not possible to replace units during operation due to ring structure

Example

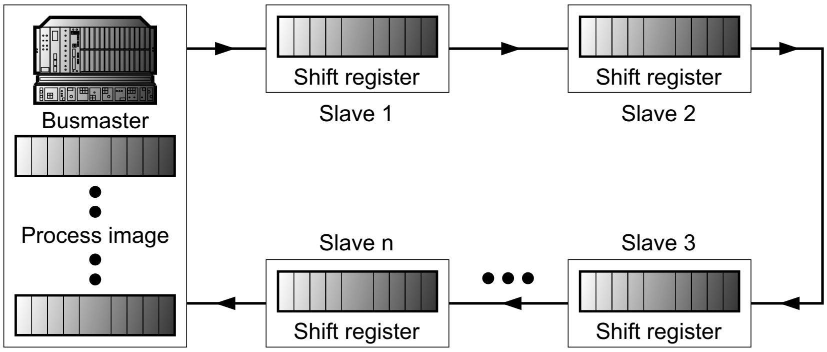

Fig. 85: Block diagram of an INTERBUS-S fieldbus design

6.6.4 Ethernet in fieldbus applications

The American company XEROX came out a local network with the name ETHERNET in the mid seventies that has established itself in the PC world.

However, Ethernet was not originally real-time capable and could not be used for fieldbus applications. In recent years, a large number of companies have provided the basis for the use in industrial automation engineering with the development of real-time capable profiles.

Application examples:

PROFINET	: SIEMENS AG
MODBUS TCP	: AEG Schneider
Powerlink	: B&R
EtherCAT	: Beckhoff
EtherNet / IP	: Rockwell Automation / Allen Bradley

6.6.5 Axis-to-axis communication

If multiple axes are linked directly together, the axes can exchange both time-critical and cyclic data as well as acyclic parameter information.

One example application is phase-synchronous operation where the position of the master is transferred synchronized to the slave. An "electronic shaft" can be implemented in this way, for example.

For axis-to-axis communication, CAN or serial interfaces can be considered depending on the speed of the data transfer.

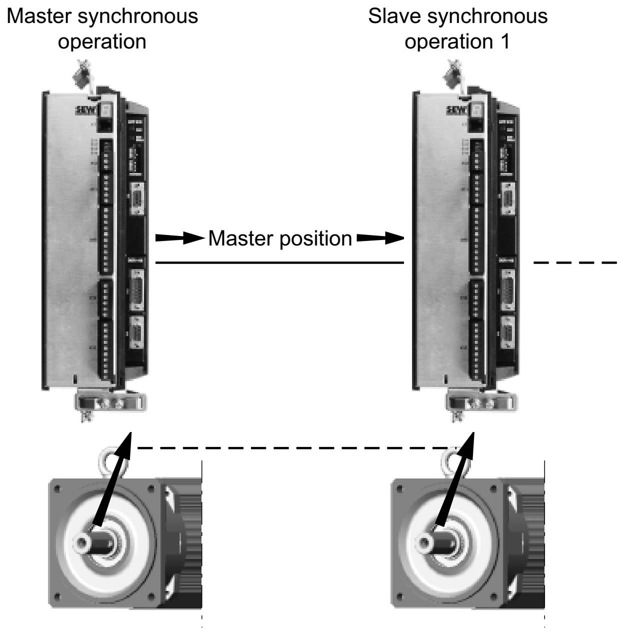

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Fig. 86: Basic design of an electronic shaft with synchronized slave (phase-synchronous operation)

The axis can also be linked via a fieldbus in order to communication with a machine control, such as a PLC. The fieldbus and the axis-to-axis communication do not influence each other in doing so.

6.6.6 Diagnostics bus

If the serial connection from axis to axis is additionally connected to a PC, it is possible to use the network as a diagnostics bus. For this, the PC exchanges parameter data with the axes over the parameter channel and visualizes the data on the PC.

The user can use a diagnostics tool to perform the following:

- Startup the axes
- Diagnose the axes
- Read unit parameters from the axes and save them on the PC

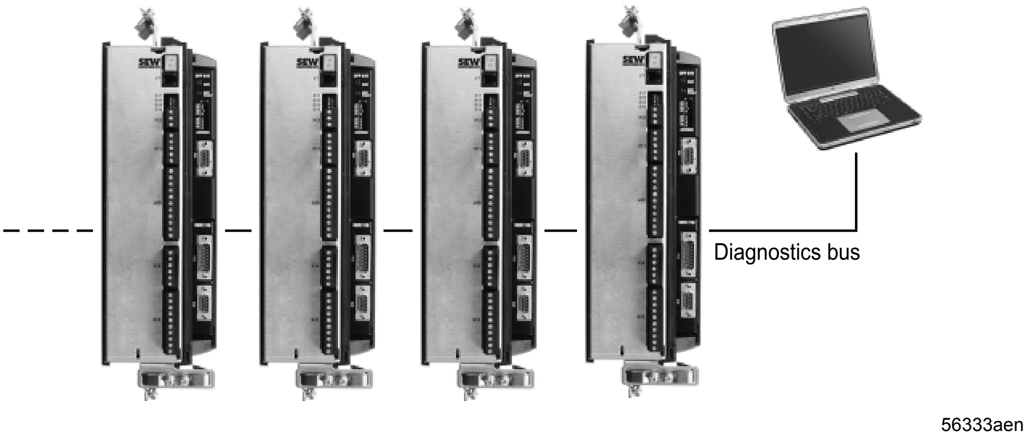


Fig. 87: Diagnostics bus

In addition to serial interfaces, CAN- and Ethernet-based systems are being used more and more as diagnostic buses.

6.7 Definitions

Term/abbreviation	Definition/explanation
Derating	Performance reduction due to thermal load
ESD	Electrostatic discharge
Surge	Impulse voltage
Burst	Rapid, transient interference
EMC	**E**lectro**m**agnetic **c**ompatibility
EMI	**E**lectro**m**agnetic **i**nterference
EME	**E**lectro**m**agnetic **e**mission
Polling	Polling for synchronizing during data transfer

7 Servo Gear Units

The gear unit, in its function as a converter of torque and speed, is the central component in a geared servomotor.

7.1 Servo gear unit requirements

Special requirements are placed on servo gear units due to cycle times that are usually short and the high accelerations that result in today's servo applications.

- Low mass moment of inertia
- Low circumferential backlash
- High torsional rigidity
- High efficiency
- Transfer of very high torques due to high acceleration values
- Precision balanced
- Ideally integer gear ratios
- Long life and low maintenance
- Compact and lightweight

Servo gear unit requirements depending on the application are displayed in the following table.

Application	Mean output speed	Max. overhung load	Max. acceleration torque	Braking torque	Mass moment of inertia	Rigidity	Uniform travel	Food-grade drives	Explosion-proof version
Wood processing		x	x	x	x	x			x
Printing machines	x				x	x	x		x
Machine tools									
Tool changers			x	x	x	x			
Rotary tables					x	x	x		
Beverage industry									
Bottlers			x	x				x	
Transfer axes		x		x		x			
CD industry			x		x	x	x		
Packaging	x		x		x	x	x	x	

The gear unit must have a low mass moment of inertia in order to implement a highly dynamic drive. Especially for drives that accelerate quickly, dynamic gear units with high degrees of efficiency are essential.

For positioning operation, circumferential backlash must be as low as possible and torsional rigidity must be high. Gear units were developed especially for the requirements of servo technology with circumferential backlash of only 3 – 6 angular minutes.

7.2 General gear unit overview

We distinguish between the following gear unit types depending on the direction of power flow:

- Coaxial gear units
- Parallel shaft gear units
- Right-angle gear units

In the case of coaxial and parallel shaft gear units, the input and output shaft are located in the same plane – the power flow is in a straight line. Consequently, the power flow is linear. With right-angle gear units, the input and output shafts are located perpendicular to one another. The power flow is vectored at a right angle.

Gear unit types		
Wheel gear units	**Belt drive gear units**	**Chain gear units**
Helical	Toothed belt	Roller chain
Planetary	Flat belt	Toothed chain
Bevel	V-belt	

The gear unit types most used in servo technology are described briefly in the following sections.

7.2.1 Planetary servo gear units

Planetary gear units are used especially often for servo applications.

The distribution of load between several planet wheels results in a power-to-weight ratio that is significantly higher than in helical gear units, meaning that the units are more compact. Due to optimized gearing geometry and the closest possible manufacturing tolerances, planetary gear units can ensure torsion angles between one and six angular minutes, or even just one angular minutes in special cases. Amply rated shaft diameters guarantee high torsional rigidity and thus a high level of positioning accuracy. In addition, planetary gear units have a high level of efficiency and are low noise and low maintenance.

By mounting to the motor directly, it is possible to obtain especially compact dimensions. The new geared servomotors from SEW-EURODRIVE make it possible to mount servo gear units directly to the synchronous servomotors from SEW-EURODRIVE without an adapter. These integrated geared servomotors offer shaft-hub connections that are all positive and free from backlash.

The most important features of low-backlash planetary gear units from SEW-EURODRIVE:

- High permitted torques
- High efficiency levels
- High torsional rigidity
- Reliable and long life
- Finely stepped, gear ratios up to 1:100
- Low operating temperature
- Constantly low circumferential backlash
- High permitted overhung loads

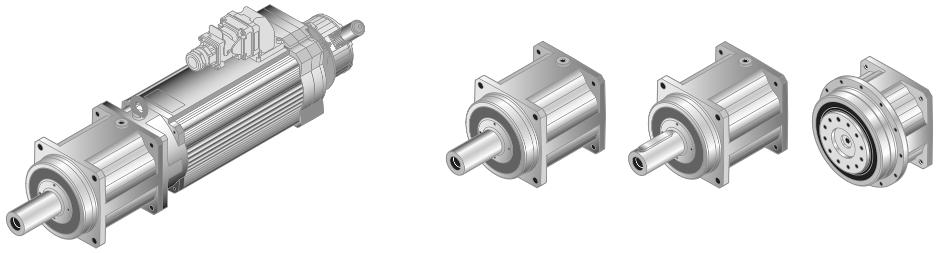
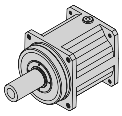
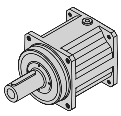
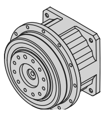


Fig. 88: Example of a planetary servo gear unit

PSF.. planetary servo gear units with B5 output flange for mounting		
Type		**Meaning**
	PSF..	Planetary servo gear unit with solid shaft
	PSKF..	Planetary servo gear unit with solid shaft and key
	PSBF..	Planetary servo gear unit with flange block shaft according to EN ISO 9409

7.2.2 Helical-bevel servo gear unit

Helical-bevel servo gear units of the BSF.. series from SEW-EURODRIVE are two-stage gear units for applications in servo technology. They consist of a helical gear stage at the input and an axially shifted helical-bevel gear stage at the output. The housing consists of one piece. Helical-bevel servo gear units can be mounted directly to the motor as well, resulting in especially compact dimensions.

The most important features of helical-bevel servo gear units from SEW-EURODRIVE:

- High permitted torques
- High permitted overhung loads
- Reliable and long life
- Finely stepped, gear ratios up to 1:40
- Wear-free gearing
- Highest degree of variability
- Compact and lightweight design
- Constantly low circumferential backlash

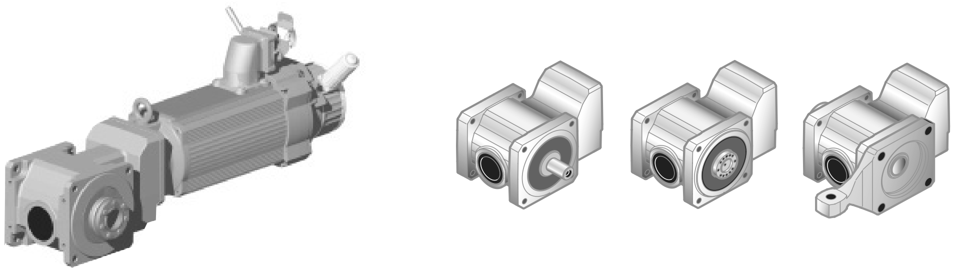
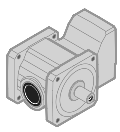
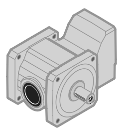
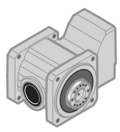
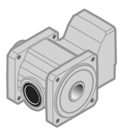


Fig. 89: Example of a helical-bevel servo gear unit

Types of low-backlash helical-bevel gear units

BSF.. helical-bevel servo gear units with B5 output flange for mounting		
Type		**Meaning**
	BSF..	Helical-bevel servo gear unit with solid shaft
	BSKF..	Helical-bevel servo gear unit with solid shaft and key
	BSBF..	Helical-bevel servo gear unit with flange block shaft according to EN ISO 9409
	BSHF..	Helical-bevel servo gear unit with hollow shaft and shrink disc opposite the output end

7.2.3 Helical gear units

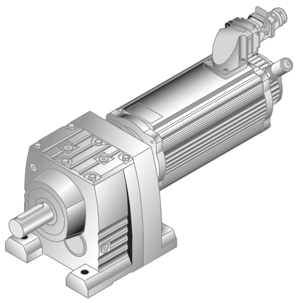
As helical gear units can be produced affordably and satisfy a large number of requirements due to their simple and robust design, they are used in many applications.

In parallel-shaft helical gear units, the input and output shafts are in parallel with one another. This makes the entire drive short and narrow, which proves to be advantageous where little space is available.

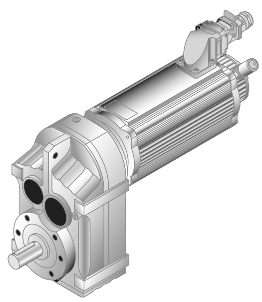
Helical gear units are usually used in servo technology in low-backlash designs.

The most important features of helical gear units:

- Favorable price
- Many possible combinations
- Large gear ratio and torque range; gear unit design: one, two, and three stage; multi-stage gear unit
- High efficiency
- Reduced circumferential backlash optional



Helical geared motor



Parallel shaft helical geared motor

Fig. 90: Examples of helical geared motors

7.2.4 Helical-bevel gear units

Helical-bevel gear units are often used when there is a limited amount of space available for installation because they can be very compact due to the angular output.

Helical-bevel gear units are available with:

- Hollow shaft with key
- Hollow shaft with shrink disk
- Solid shaft
- Splined design

Additionally, both the mounting flange and shaft-mounted versions offer many options for integration in various systems. Low-backlash helical-bevel gear units are suited for servo applications due to the high accelerations and frequent load variation.

The most important features of helical-bevel gear units:

- Low space requirement due to angular output, short length in the axial direction
- Optimum integration in the system
- Extensive range of mounting positions and versions
- Many possible combinations
- Large gear ratio and torque range; gear unit design: three stage; multi-stage gear unit
- High efficiency
- High starting torque

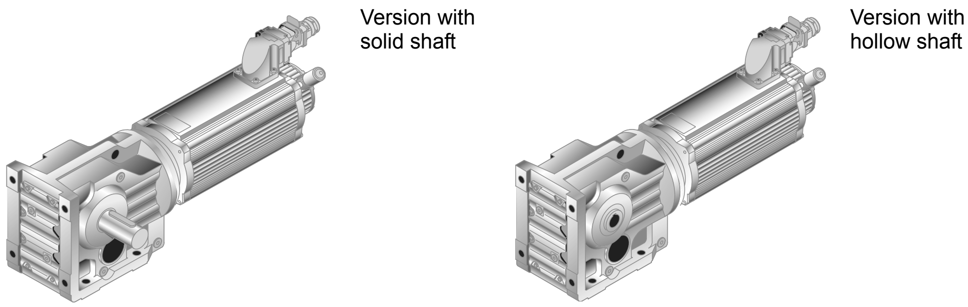


Fig. 91: Example of helical-bevel geared motors

8 Project Planning

8.1 General information

For project planning for a servo drive, in addition to a travel diagram that describes the exact travel cycle, a large number of additional specifications must be made about the operating and environmental conditions. It is first necessary to have data for the machine to be driven such as mass, setting range, speed, information about the mechanical design and so on in order to select the drive correctly.

The appropriate servo drive can be determined with the calculated torques and speeds of the drive while taking other mechanical requirements such as environmental and operating conditions into account.

Project planning for a servo drive and a linear servomotor is illustrated using a practical example for each in the following sections.

8.2 Drive and gear unit selection data

Certain data is essential to specify the components for the drive precisely:

Data for the selection of a geared servomotor

Data for the selection of a geared servomotor		
Δ S	Positioning accuracy	[mm]
cdf	Cyclic duration factor	%
H	Installation altitude	[m above sea level]
η_{gear}	Efficiency of the gear unit	–
η_L	Load efficiency	–
i	Gear unit reduction ratio	–
I_N	Rated current (nominal)	[A]
I_{eff_motor}	Effective motor current	[A]
$I_{R\_inverter}$	Rated current of the servo inverter	[A]
IP..	Required enclosure	–
	Circumferential backlash	[']
ϑ_{amb}	Ambient temperature	[°C]
J_{ext}	Mass moment of inertia (external) reduced on motor shaft	[kgm^2]
J_{gear}	Mass moment of inertia of the gear unit	[kgm^2]
J_{Mot}	Mass moment of inertia of the motor	[kgm^2]
k	Inertia ratio J_{ext} / J_{Mot}	–
M_{acc}	Acceleration torque	[Nm]
M_N	Rated torque (nominal)	[Nm]
M1 – M6	Mounting position	–
$M_1...M_n$	Output torque in time period t_1 to t_n	[Nm]
$M_{o\ cub}$	Cubic output torque	[Nm]
$M_{o\ max}$	Maximum output torque	[Nm]
M_R	Rated torque	[Nm]
M_{Br_motor}	Breaking torque of the motor	[Nm]
M_{DYN}	Dynamic limit torque of the servomotor	[Nm]
M_{in}	Input torque	[Nm]
$M_{in\ max}$	Maximum input torque	[Nm]
M_{eff}	Effective torque requirement (in relation to the motor)	[Nm]
M_{eff_motor}	Effective motor torque	[Nm]
M_{gear}	Gear unit torque	[Nm]
M_{max}	Maximum output torque assumed for the drive in project planning	[Nm]
M_{Mot}	Motor torque	[Nm]
M_{e_stop}	Permitted emergency stop torque	[Nm]
$M_{e\_stop\_appl}$	Emergency stop torque of the application	[Nm]
M_{stat}	Static motor torque	[Nm]
M_{stat_motor}	Motor torque during constant travel	[Nm]
M_{tn}	Torque in section n	[Nm]
M_{THeff}	Effective torque in reference to the temperature rise in the gear unit	[Nm]
M_{THERM}	Thermal torque	[Nm]
n_o	Output speed	[min^{-1}]
$n_{o\ max}$	Maximum output speed	[min^{-1}]
$n_{o\ m}$	Mean output speed of the gear unit	[min^{-1}]
n_{in}	Input speed	[min^{-1}]

Data for the selection of a geared servomotor		
$n_{in\ max}$	Maximum input speed	[min^{-1}]
n_C	Speed constant	[min^{-1}]
n_{max}	Maximum speed	[min^{-1}]
n_{Mot}	Motor speed	[min^{-1}]
n_N	Rated speed (nominal)	[min^{-1}]
n_x	Mean speed in section x	[min^{-1}]
P_{Br}	Braking power	[W]
P_{Br_peak}	Peak braking power	[W]
S..	Operating mode	–
$t_1...t_n$	Time period 1 to n	[min]
t_{Brn}	Braking time in section n	[s]
t_{Cycle}	Cycle time	[s]

Data for the selection of a linear servo drive

Data for the selection of a linear servo drive		
μ	Coefficient of friction	–
α	Incline angle of travel distance	[°]
a_{max}	Maximum acceleration	[ms^{-2}]
cdf	Cyclic duration factor	[%]
F_A	Maximum required thrust	[N]
F_D	Magnetic attraction force	[N]
F_E	Effective force outside the total cycle	[N]
F_W	Weight	[N]
F_i	Force present in partial cycle	[N]
F_{max}	Maximum force	[N]
F_{mm}	Maximum thrust of the motor	[N]
F_{rated}	Rated force (nominal)	[N]
F_f	Maximum friction force	[N]
F_{table}	Force from inverter table	[N]
F_t	Thrust force	[N]
F_{tmax}	Maximum thrust	[N]
F_a	Additional process force	[N]
g	Gravitational acceleration	[ms^{-2}]
I_{rated}	Rated current (nominal)	[A]
k_N	Force constant	[NA^{-1}]
L_p	Length of the projected primary	[mm]
m_L	Mass of an axis to be moved	[kg]
m_P	Mass of primary	[kg]
m_A	Additional mass	[kg]
P_{max}	Maximum power of the braking resistor	[kW]
P_n	Mean power of the braking resistor	[kW]
s	Travel distance	[mm]
S	Length of the projected travel distance	[mm]
S_l	Limit switch range	[mm]
s_s	Length of secondary	[mm]

Data for the selection of a linear servo drive		
t	Total cycle time including rest periods	[s]
t_i	Cycle duration (for F_i)	[s]
t_n	Time in period n	[s]
v_{max}	Maximum velocity of an axis	[ms^{-1}]

8.3 Project planning procedure of a geared servomotor

The project planning procedure is organized as follows:

- Gear unit selection, see also figure 92
  - [1] Gearing
  - [2] Bearing
  - [3] Thermal properties

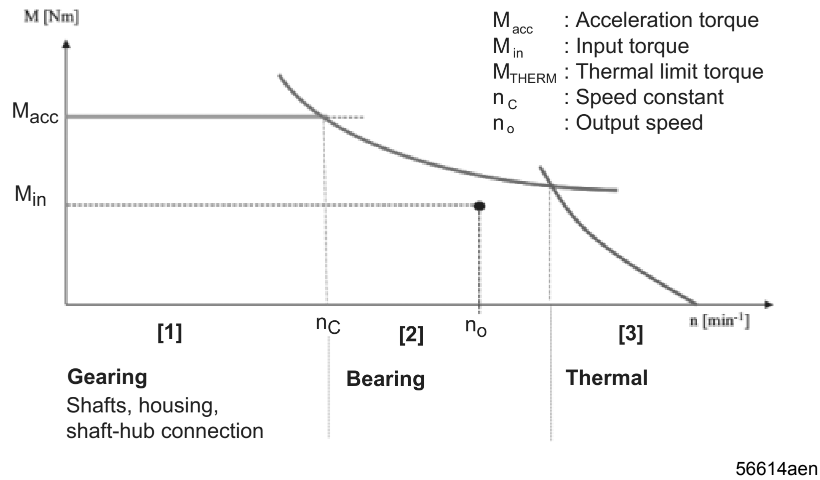
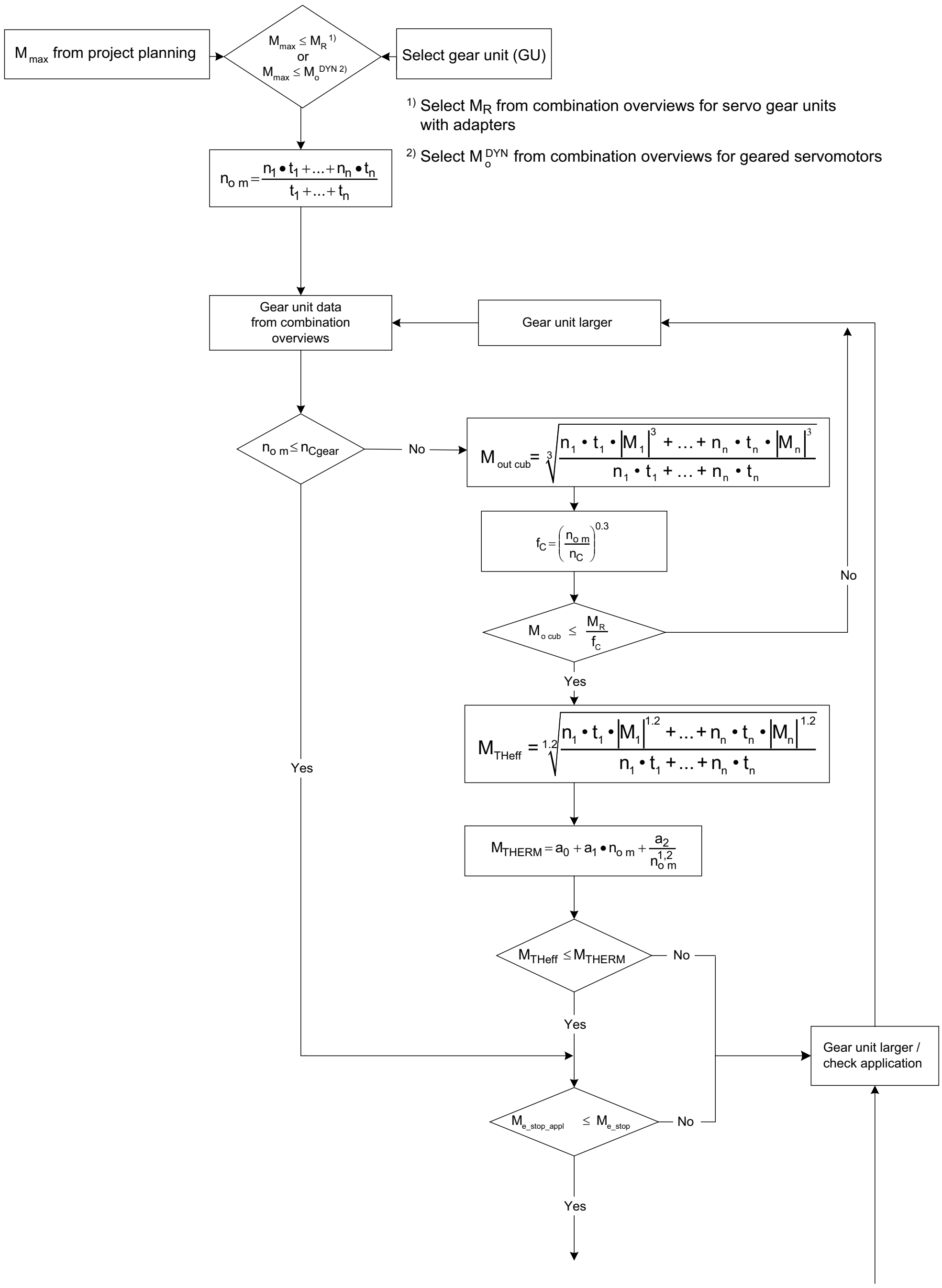


Fig. 92: Three-stage project planning procedure

- Motor selection
- Servo inverter selection
- Braking resistor selection

The following flowcharts show a schematic view of the project planning procedure of a helical-bevel servo gear unit for a positioning drive in S3 operation.

Project planning procedure, part 1, servo gear units



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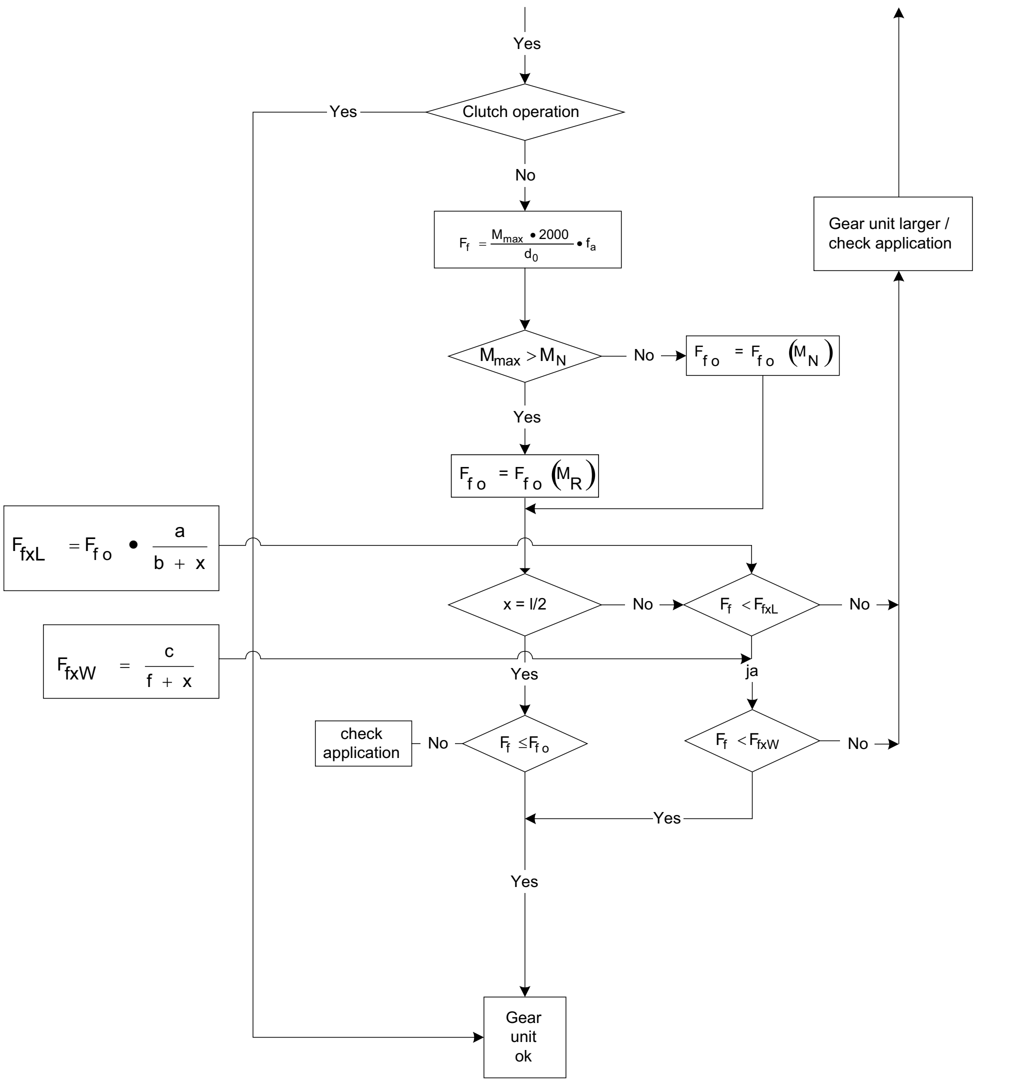
Project planning procedure, part 2, servo gear units



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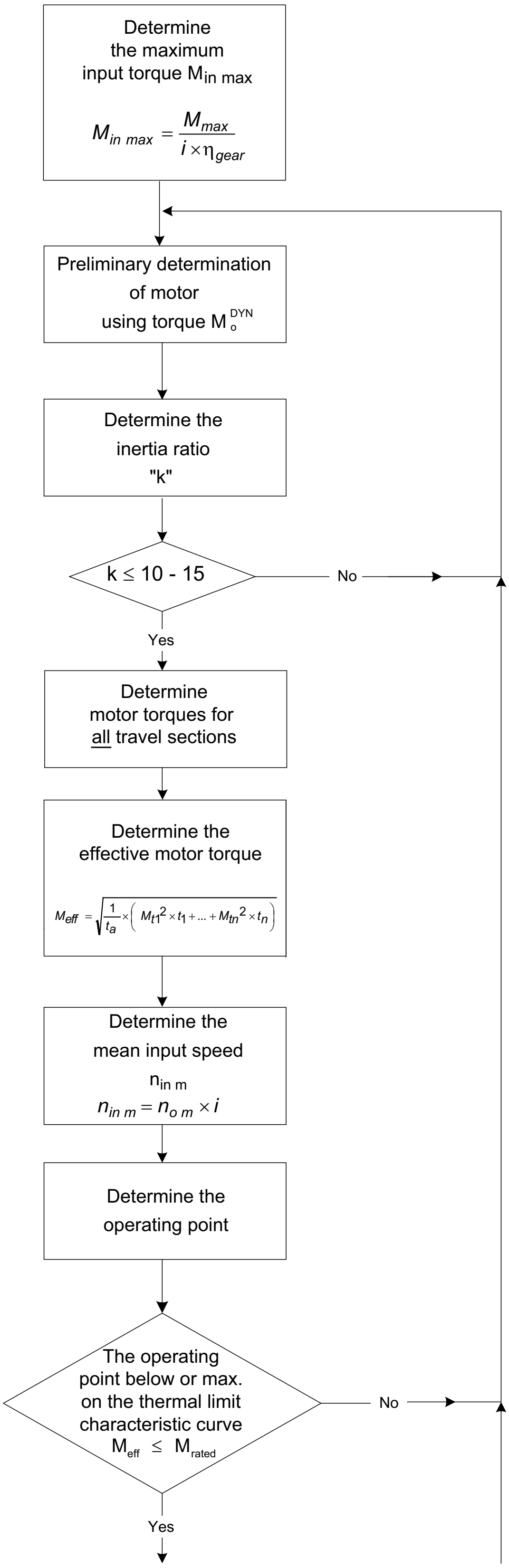
Project planning procedure, part 3, servomotors



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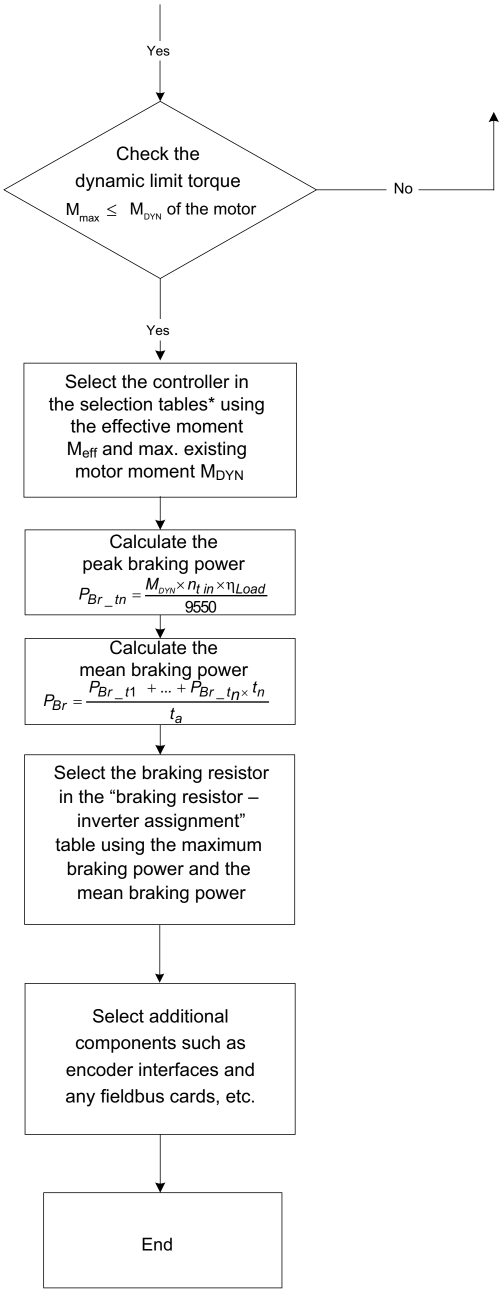
Project planning procedure, part 4, servomotors



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* MOVIDRIVE® system manual

8.4 Example of project planning for a geared servomotor

It is first necessary to have data on the machine to be driven (mass, speed, setting range, etc.) to select the drive correctly. This data helps determine the required power, torque and speed. The following example of project planning for a geared servomotor and respective servo inverter illustrates the procedure in detail.

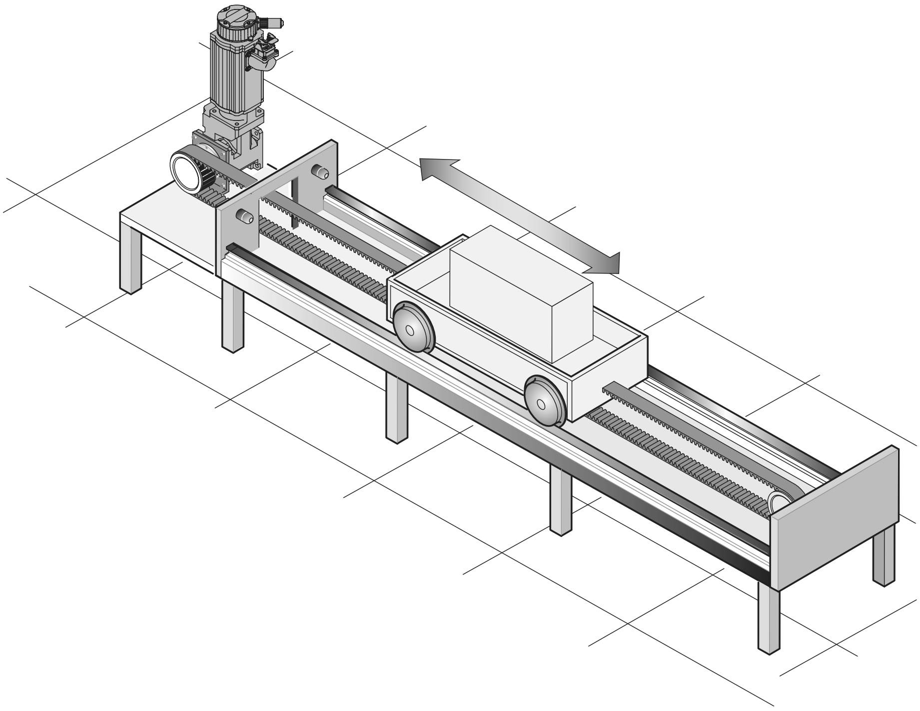

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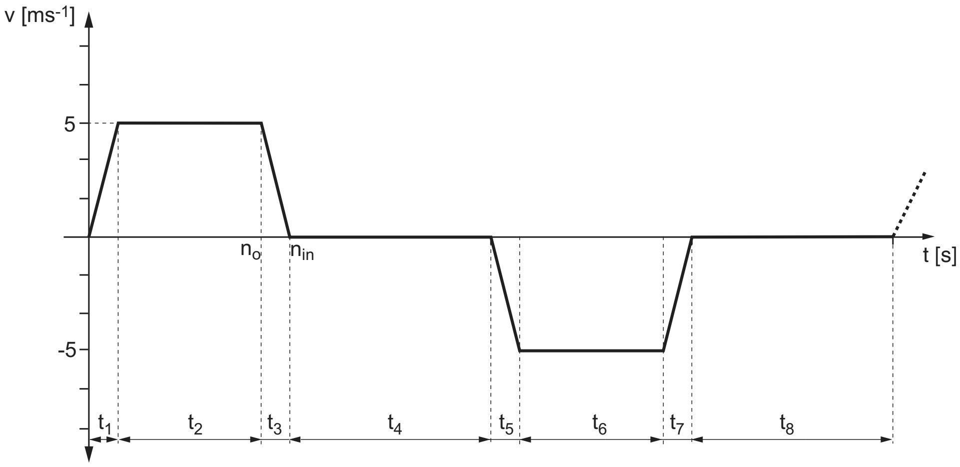
Fig. 93: Project planning example: Selection of a BSF.. gear unit with direct motor mounting

Reference data:

Weight of the load:	m_{Load} =	150 kg
Weight of the carriage:	$m_{Trolley}$ =	100 kg
Traveling velocity:	v =	5 ms^{-1}
Acceleration:	a =	10 ms^{-2}
Deceleration:	–a =	10 ms^{-2}
Deceleration for EMERGENCY STOP:	–a =	16.8 ms^{-2}
Diameter of the carrying wheel:	D_L =	250 mm
Resistance to motion:	F_F =	100 N/t
Load efficiency:	η_L =	0,9
Ambient temperature:	ϑ =	20°C
Required positioning accuracy:		0.7 mm
Mechanical positioning accuracy:		0.3 mm
Required EMC limit value class:		A
Motor type:		Synchronous servomotor
Gear unit type:		BSF..
Gear unit mounting position:		M4
Encoder type:		Absolute value encoder
Connection to fieldbus system of type:		Profibus DPV1
Transmission element factor:	f_z=	2.5

Travel diagram



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Time periods

The following time periods result from the travel cycle:

$t_1 = t_3 = t_5 = t_7 = 0.5$ s

$t_2 = t_6 = 2.0$ s

$t_4 = t_8 = 1.5$ s

Mean speed

The mean speed in section x is calculated as follows:

$$n_x = \frac{n_o + n_{in}}{2}$$

Selection of the servo gear unit

Step 1: Preliminary determination of the gear unit reduction ratio

$$n_{o\ max} = \frac{v_{max}}{D_L \times \pi}$$

$$n_{o\ max} = \frac{5\ \text{m/s}}{0.25\ \text{m} \times \pi} = 6.366\ \text{1/s} = 382\ \text{1/min}$$

The gear unit reduction ratio is determined by approximation by means of the maximum output speed and an assumed rated motor speed of n_R = 4500 1/min. It has proven to be advantageous to take into account a speed reserve of 10%.

$$i_{preliminary} = \frac{n_R - 10\ \%}{n_{o\ max}}$$

$$i_{preliminary} = \frac{4050\ \text{1/min}}{382\ \text{1/min}} = 10.6$$

The selected gear unit reduction ratio is: i = 10.

The maximum input speed $n_{in\ max}$ is calculated based on the selected gear unit reduction ratio:

$$n_{in\ max} = i \times n_{o\ max}$$

$$n_{in\ max} = 10 \times 382\ 1/min = 3820\ 1/min$$

Step 2: Determine the static and dynamic torques

Dynamic torque in section t_1:

$$M_{DYN1} = \frac{m \times a \times D_L}{\eta_L \times 2}$$

$$M_{DYN1} = \frac{(150\ kg + 100\ kg) \times 10\ m/s^2 \times 0.25\ m}{0.9 \times 2} = 347\ Nm$$

Dynamic torque in section t_3:

The degree of efficiency benefits the dynamic torque in section t_3 as there is deceleration.

$$M_{DYN3} = \frac{m \times (-a) \times \eta_L \times D_L}{2}$$

$$M_{DYN3} = \frac{(150\ kg + 100\ kg) \times (-10\ m/s^2) \times 0.9 \times 0.25\ m}{2} = -281\ Nm$$

Static torque:

The static torque is calculated using the resistance to motion and must be taken into account in every travel section.

During acceleration:

$$M_{stat1} = \frac{F_F \times D_L \times m}{\eta_L \times 2}$$

$$M_{stat1} = \frac{100\ N/t \times 0.25\ m \times (0.15\ t + 0.1\ t)}{0.9 \times 2} = 3.5\ Nm$$

During deceleration:

$$M_{stat3} = F_F \times \frac{D_L}{2} \times m \times \eta_L$$

$$M_{stat3} = 100\ N/t \times \frac{0.25\ m}{2} \times (0.15\ t + 0.1\ t) \times 0.9 = 2.8\ Nm$$

Step 3: Determine the maximum output torque $M_{o\,max}$

During acceleration:

$$M_{o\,max1} = M_{stat1} + M_{dyn1}$$

$$M_{o\,max1} = 3.5\text{ Nm} + 347\text{ Nm} = 351\text{ Nm}$$

During deceleration:

$$M_{o\,max3} = M_{stat3} + (-M_{dyn1})$$

$$M_{o\,max3} = 2.8\text{ Nm} - 281\text{ Nm} = -278\text{ Nm}$$

Step 4: Select the gear unit size

The combination table of the catalog "Low-Backlash Geared Servomotors (BSF.., PSF..)" is used for the preliminary selection of the servo gear unit.

Preliminary gear unit selection: **BSF 502**

Selection criterion: $M_{o\,max}$ = 351 Nm

Requirement: $M_R \geq M_{o\,max}$

375 Nm ≥ 351 Nm → **requirement fulfilled.**

Step 5: Determine the mean output speed

$$n_{o\,m} = \frac{n_1 \times t_1 + \ldots + n_n \times t_n}{t_1 + \ldots + t_n}$$

$$n_{o\,m} = \frac{\frac{382\text{ min}^{-1}}{2} \times 0.5\text{ s} + 382\text{ min}^{-1} \times 2\text{ s} + \frac{382\text{ min}^{-1}}{2} \times 0.5\text{ s}}{0.5\text{ s} + 2\text{ s} + 0.5\text{ s} + 1.5\text{ s}} = 212\text{ min}^{-1}$$

Requirement: $n_{o\,m} \leq n_k$

212 min^{-1} ≤ 130 min^{-1} → **requirement not fulfilled.**

To ensure that the selection of the gear unit is optimal with respect to the load, the mean output speed must be lower or maximally as high as the speed constant of the gear unit, n_C. If this condition is not fulfilled, then the load must be checked using the cubic moment, see step 6.

Step 6: Determine the cubic output torque $M_{o\,cub}$

$$M_{o\,cub} = \sqrt[3]{\frac{n_1 \times t_1 \times |M_1|^3 + \ldots + n_n \times t_n \times |M_n|^3}{n_1 \times t_1 + \ldots + n_n \times t_n}}$$

$$M_{o\,cub} = \sqrt[3]{\frac{0.5\text{ s} \times 191\text{ min}^{-1} \times |351\text{ Nm}|^3 + 2\text{ s} \times 382\text{ min}^{-1} \times |3.5\text{ Nm}|^3 + 0.5\text{ s} \times 191\text{ min}^{-1} \times |278\text{ Nm}|^3}{0.5\text{ s} \times 191\text{ min}^{-1} + 2\text{ s} \times 382\text{ min}^{-1} + 0.5\text{ s} \times 191\text{ min}^{-1}}} = 186.4\text{ Nm}$$

Step 7: Determine the speed factor f_C

The quotient from the mean output speed and the speed constant n_C form the speed factor f_C. The speed factor is required to check the cubic output torque. It must be less than or maximally as large as the rated torque of the gear unit.

$$f_C = \left(\frac{n_{o\,m}}{n_C}\right)^{0.3}$$

$$f_C = \left(\frac{212\ \text{min}^{-1}}{130\ \text{min}^{-1}}\right)^{0.3} = 1.16$$

Requirement:

$$M_{o\,cub} \leq \frac{M_R}{f_C} \leq \frac{375\ \text{Nm}}{1.16} \leq 323\ \text{Nm}$$

186 Nm ≤ 323 Nm → **requirement fulfilled.**

Step 8: Determine the effective torque for checking the permitted temperature rise in the gear unit

$$M_{THeff} = \sqrt[1.2]{\frac{n_1 \times t_1 \times |M_1|^{1.2} + \ldots + n_n \times t_n \times |M_n|^{1.2}}{n_1 \times t_1 + \ldots + n_n \times t_n}}$$

$$M_{THeff} = \sqrt[1.2]{\frac{0.5\ \text{s} \times 191\ \text{min}^{-1} \times |351\ \text{Nm}|^{1.2} + 2\ \text{s} \times 382\ \text{min}^{-1} \times |3.5\ \text{Nm}|^{1.2} + 0.5\ \text{s} \times 191\ \text{min}^{-1} \times |278\ \text{Nm}|^{1.2}}{0.5\ \text{s} \times 191\ \text{min}^{-1} + 2\ \text{s} \times 382\ \text{min}^{-1} + 0.5\ \text{s} \times 191\ \text{min}^{-1}}} = 83.6\ \text{Nm}$$

Step 9: Determine the permitted thermal torque due to temperature rise in the gear unit

$$M_{THERM} = a_0 + a_1 \times n_{o\,m} + \frac{a_2}{n_{o\,m}^{1.2}}$$

$$M_{THERM} = -17.47 + (-0.316 \times 212) + \frac{119454}{212^{1.2}} = 108.6\ \text{Nm}$$

Requirement: $M_{THeff} \leq M_{THERM}$

83.6 Nm ≤ 108.6 Nm → **requirement fulfilled.**

Step 10: Compare the EMERGENCY STOP torque and the EMERGENCY STOP torque of the gear unit

Higher torques arise in the case of an emergency stop due to shorter deceleration times. Consequently, you must check whether the emergency off torque of the application ($M_{e\_stop\_appl}$) is smaller than the permitted emergency stop moment (M_{e_stop}) of the gear unit. According to the application data, an emergency stop causes the application to decelerate at 16.8 m/s².

$$M_{e\_stop\_appl} = m \times a \times \frac{D}{2}$$

$$M_{e\_stop\_appl} = (150\text{ kg} + 100\text{ kg}) \times 16.8\text{ m/s}^2 \times \frac{0.25\text{ m}}{2} = 525\text{ Nm}$$

Requirement: $M_{e\_stop\_appl} \leq M_{e\_stop}$

525 Nm ≤ 560 Nm → **requirement fulfilled.**

Step 11: Determine the overhung load

The application point for the overhung load is on the midpoint of the shaft. Due to the pre-tensioning of the toothed belt, the overhung load is based on a transmission element factor of 2.5.

$$F_f = \frac{M_{max} \times 2000}{d_0} \times f_{tr} = \frac{347 \times 2000}{250} \times 2.5 = 6940\text{ N}$$

Requirement: $M_N < M_{max} < M_R \Rightarrow F_f \leq F_{f\,o}\,(M_R)$.

⇒ 6940 N ≤ 12000 N → **requirement fulfilled.**

Selection of the servomotor

Step 12: Convert the acceleration moment at the drive to the motor side

$$M_{in\ max} = \frac{M_{o\ max}}{i \times \eta_{gear}}$$

$$M_{in\ max} = \frac{351\text{ Nm}}{10 \times 0.91} = 38.6\text{ Nm}$$

This maximum input torque is used for a preliminary motor selection, which still needs to be checked:

⇒ CM90L/BR

- J_{Mot} = 35.9×10^{-4} kgm².
- M_N = 21.0 Nm.
- n_R = 4500 1/min.

Step 13: Check the additional motor torque for acceleration

For the acceleration, the motor must deliver a certain torque to being able to accelerate itself.

$$M_{motor} = \frac{J_{motor} \times n_{max} \times 2 \times \pi}{t_o}$$

$$M_{motor} = \frac{35.9 \times 10^{-4}\text{ kgm}^2 \times 3820\text{ min}^{-1} \times 2 \times \pi}{0.5\text{ s}} = 2.9\text{ Nm}$$

Step 14: Determine the total motor moment during acceleration

$$M_{max} = M_{in\ max} + M_{motor}$$

$$M_{max} = 38.6\ \text{Nm} + 2.9\ \text{Nm} = 41.5\ \text{Nm}$$

Step 15: Determine the total motor moment during deceleration

$$M_{Br\_motor} = M_{3\ max} \times \eta_{gear} \times \frac{1}{i} + M_{motor}$$

$$M_{Br\_motor} = -278\ \text{Nm} \times 0.91 \times \frac{1}{10} + (-2.9)\ \text{Nm} = -28.2\ \text{Nm}$$

Step 16: Determine the motor torque during constant travel

$$M_{stat\_motor} = M_{stat} \times \frac{1}{i \times \eta_{gear}}$$

$$M_{stat\_motor} = \frac{3.5\ \text{Nm}}{10 \times 0.91} = 0.39\ \text{Nm}$$

Step 17: Determine the effective motor torque

If the motor torques can be determined for every travel section, the effective motor torque can be calculated. This is essential for determining the operating point (see step 18).

$$M_{eff} = \sqrt{\frac{1}{t_{Cycle}} \times (M_{t1}^2 \times t_1 + M_{t2}^2 \times t_2 + \ .... + M_{tn}^2 \times t_n)}$$

$$M_{eff} = \sqrt{\frac{(41.5\ \text{Nm})^2 \times 0.5\ \text{s} + (0.39\ \text{Nm})^2 \times 2\ \text{s} + (-28.2\ \text{Nm})^2 \times 0.5\ \text{s}}{0.5\ \text{s} + 2\ \text{s} + 0.5\ \text{s} + 1.5\ \text{s}}} = 16.7\ \text{Nm}$$

Step 18: Determine the mean speed

If the effective motor torque has been determined, the mean speed can be calculated. This is essential for determining the operating point (see step 19).

$$n = n_{o\ m} \times i$$

$$n = 212\ \text{min}^{-1} \times 10 = 2120\ \text{min}^{-1}$$

Step 19: Determine the operating point

With the operating point, it is possible to determine whether the motor is thermally overloaded in accordance with the travel diagram. For this, the mean motor speed and the effective motor torque are entered into the "Thermal limit characteristic curve" diagram; see figure 94. The intersection is the exact operating point. It must lie below or maximally on the thermal limit characteristic curve.

To ensure operational reliability, it is recommended to maintain a certain distance between the operating point and the thermal limit characteristic curve. This secures a certain reserve for any necessary changes such as higher acceleration values, higher load, and so on.

For this reason, the CM90L motor is equipped with a VR forced cooling fan: CM90L/VR.

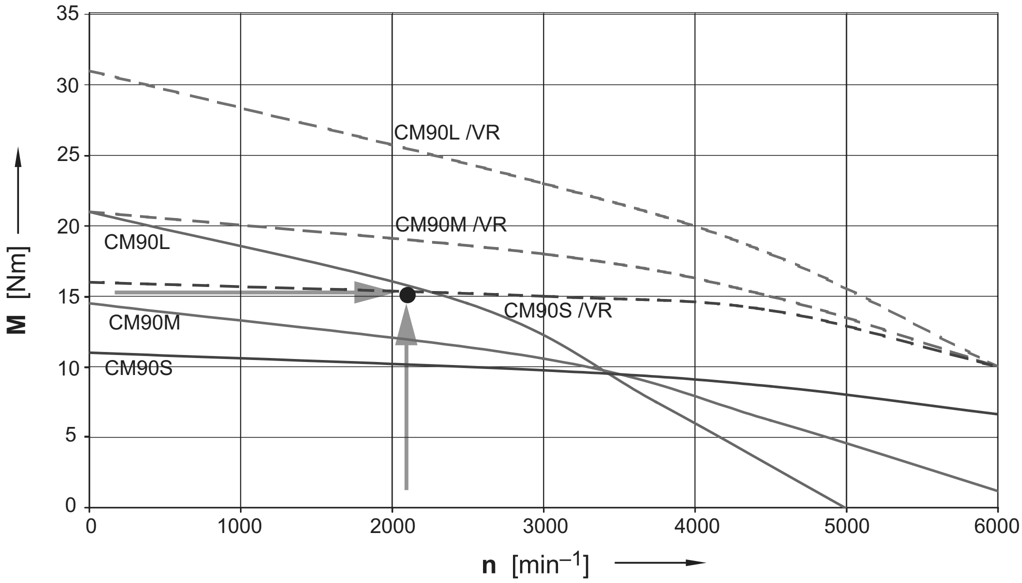

Fig. 94: Thermal characteristic curve of CM90L/VR with operating point of example application

Step 20: Determine the maximum operating point

Using the maximum moment and the associated speed in every travel section, the maximum operating point or operating points are entered in the "Dynamic limit characteristic curve" diagram; see figure 95. Note that the operating point(s) must lie below or maximally on the dynamic limit characteristic curve.

To ensure operational reliability, it is recommended to maintain a certain distance between the operating point and the dynamic limit characteristic curve. This secures a certain reserve for any necessary changes such as changes to the travel diagram, higher load, and so on.

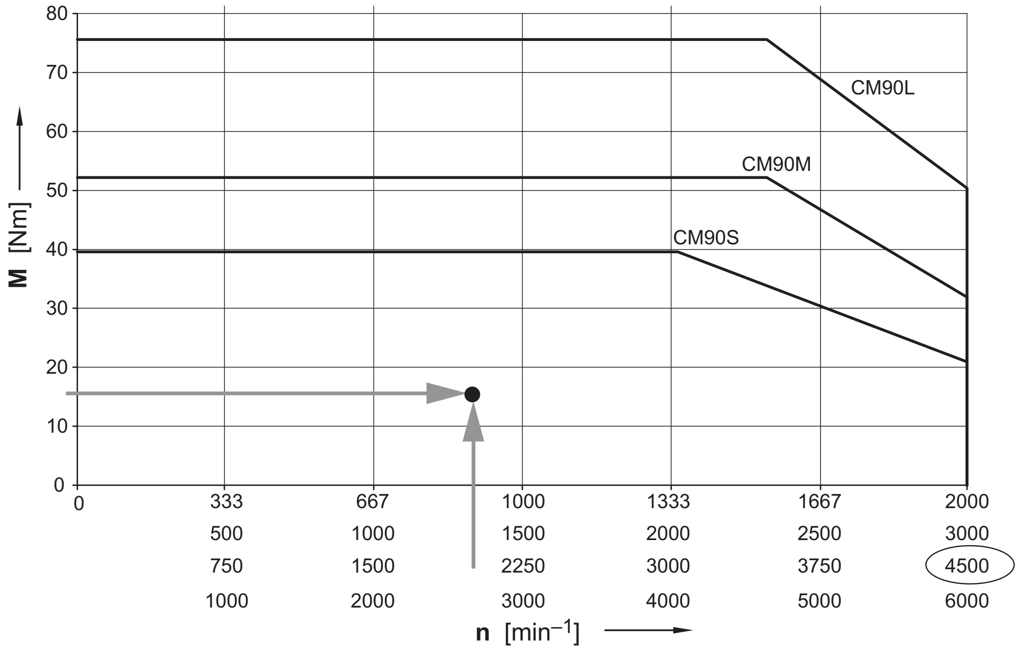

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Fig. 95: Dynamic characteristic curve of CM90L/VR with max. operating point of example application

Note that the maximum available torque drops, particularly in the upper speed range.

Step 21:
Check the mass inertia ratio "k"

The ratio of external to internal mass inertia influences the controller results greatly and cannot be disregarded. The inertia ratios according to the following table cannot be exceeded.

Driveline	Control characteristics	Inertia ratio J_{ext} / J_{Mot}
Forged gear rack, reduced-backlash gear unit	Low-backlash and low-elasticity drive	$J_{ext} / J_{Mot} < 15$
Toothed belt, reduced-backlash gear unit	Common servo applications	$J_{ext} / J_{Mot} < 15$
Toothed belt, standard gear unit	Standard applications, couplings with torque buffer	$J_{ext} / J_{Mot} < 10$

Reduction of the inertia ratio using the motor speed or the gear unit reduction ratio offers hardly any advantage with respect to control starting at the value $J_{ext} / J_{Mot} < 8$.

$$J_{ext} = 91.2 \times m \times \left(\frac{v}{n_{Mot}}\right)^2$$

$$J_{ext} = 91.2 \text{ x } 250 \text{ kg x } \left(\frac{5 \text{ m/s}}{3820 \text{ min}^{-1}}\right)^2 = 390 \text{ x } 10^{-4} \text{ kgm}^2$$

$$k = \frac{J_{ext}}{J_{Mot}}$$

$$k = \frac{390 \text{ x } 10^{-4} \text{ kgm}^2}{35.9 \text{ x } 10^{-4} \text{ kgm}^2} = 10.9$$

Requirement: $J_{ext} / J_{Mot} < 15$

10.9 < 15 → **requirement fulfilled.**

Step 22:
Determine the acceleration torque due to the mass inertia of the gear unit

$$M_{gear} = \frac{J_{gear} \text{ x } n_{max} \text{ x } 2 \text{ x } \pi}{t_a}$$

$$M_{gear} = \frac{4 \text{ x } 10^{-4} \text{ kgm}^2 \text{ x } 3820 \text{ min}^{-1} \text{ x } 2 \text{ x } \pi}{0.5 \text{ s}} = 0.9 \text{ Nm}$$

Step 23: Select the servo inverter

A servo inverter can now be selected according to the motor-servo inverter assignment table using the effective and the maximum motor torque.

$$I_{eff\_motor} = \frac{I_N \times M_{eff\_motor}}{M_N}$$

$$I_{eff\_motor} = \frac{21.6\ \text{A} \times 16.7\ \text{Nm}}{21\ \text{Nm}} = 17.2\ \text{A}$$

Requirement: $I_{eff\_motor} \leq I_{R\_inverter}$

17.2 A ≤ 32 A → **requirement fulfilled.**

n_R [min^{-1}]	Motor	M_{max} [Nm]	MOVIDRIVE®									
			0110	**0150**	**0220**	**0300**	**0370**	**0450**	**0550**	**0750**	**0900**	**1100**
			24 [A]	32 [A]	46 [A]	60 [A]	73 [A]	89 [A]	105 [A]	130 [A]	170 [A]	200 [A]
2000	**CFM71S**	M_{max}										
	CFM71M											
	CFM71L											
	CFM90S											
	CFM90M		52.5									
	CFM90L		70.3	75.8								
	CFM112S		76.2	81.9								
	CFM112M		79.3	99.6	108.0							
	CFM112L		80.3	104.9	141.5	156.8						
	CFM112H		80.1	106.5	150.3	189.2	220.1	237.0				
3000	**DFS56M**	M_{max}										
	DFS56L											
	DFS56H											
	CFM71S											
	CFM71M											
	CFM71L		31.5									
	CFM90S		39.2									
	CFM90M		47.8	51.6								
	CFM90L		51.1	65.6	75.6							
	CFM112S		54.8	69.8	81.9							
	CFM112M		54.0	70.7	95.7	108.0						
	CFM112L		53.9	71.6	101.0	126.9	147.4	156.8				
	CFM112H		56.6	75.7	108.6	139.9	167.0	197.1	223.2	237.0		
4500	**DFS56M**	M_{max}										
	DFS56L											
	DFS56H											
	CFM71S											
	CFM71M		21.3									
	CFM71L		30.3	31.2								
	CFM90S		33.6	39.2								
	CFM90M		34.6	44.5	52.1							
	CFM90L		34.7	45.8	63.4	75.0						
	CFM112S		37.4	49.2	67.5	81.9						
	CFM112M		37.1	49.4	69.6	87.4	101.5	108.0				
	CFM112L		35.0	46.8	67.2	86.9	104.1	123.5	140.7	156.8		
	CFM112H				70.9	92.5	112.1	135.5	157.7	189.4	231.6	237.0

Step 24: Select the components

Depending on the EMC limit value class observed, additional measures may be required in addition to the EMC-compliant installation. The following solution options for the supply system and the motor are available depending on the limit value class.

As the limit value class A is observed in our project planning example, an output choke is selected for the motor and a line filter for the supply system (see the following table).

Output choke:

Limit value class A

Three options are available for EMC-compliant installation in accordance with EN 55011, **limit value class A**, depending on the system configuration:

Limit value class A	On the motor	On the supply system	
	Sizes 0 to 6	Sizes 0 to 2	Sizes 3 to 6
First option	HD... output choke	No action needed	NF...-... line filter
Second option	Shielded motor line	No action needed	NF...-... line filter
Third option	HF... output filter	No action needed	NF...-... line filter

Limit value class B

Three options are available for EMC-compliant installation in accordance with EN 55011, **limit value class B**, depending on the system configuration:

Limit value class B	On the motor	On the supply system
	Sizes 0 to 5	Sizes 0 to 5
First option	HD... output choke	NF...-... line filter
Second option	Shielded motor line	NF...-... line filter
Third option	HF... output filter	NF...-... line filter

The output choke can be selected from the respective overview table in the MOVIDRIVE® system manual.

Output choke type	HD001	HD002	HD003	HD004
Part number	813 325 5	813 557 6	813 558 4	816 885 7
Max. power loss P_{Vmax}	15 W	8 W	30 W	100 W
For cable cross sections/connections	1.5...16 mm²	≤ 1.5 mm²	≥ 16 mm²	M12 terminal studs

The output choke is selected according to the cable cross section of the motor line, and therefore the following was selected: output choke type HD001.

Line filter

The lime filter must also be selected using the selection table in the MOVIDRIVE system manual.

When selecting the line filter, ensure that the supply voltage and the utilization fulfill the requirements of the application.

Line filter type	NF009-503	NF014-503	NF018-503	NF035-503	NF048-503
Part number	827 412 6	827 116 X	827 413 4	827 128 3	827 117 8
Rated voltage V_R	3 × 500 V_{AC} +10 %, 50/60 Hz				
Rated current I_R	9 A_{AC}	14 A_{AC}	18 A_{AC}	35 A_{AC}	48 A_{AC}
Power loss at I_R P_V	6 W	9 W	12 W	15 W	22 W
Earth-leakage current at V_R	< 25 mA	< 25 mA	< 25 mA	< 25 mA	< 40 mA
Ambient temperature ϑ_A	–25 ... +40 °C				
Enclosure	IP 20 (EN 60529)				
Connections L1-L3/L1'-L3' PE	4 mm^2 M5 stud			10 mm^2 M5/M6 stud	
Assignment to 400/500 V units (MDX60/61B...-5_3)					
Rated operation (100 %)	0005...0040	0055/0075	–	0110/0150	0220
With increased power (VFC, 125 %)	0005...0030	0040/0055	0075	0110	0150
Assignment to 230 V units (MDX61B...-2_3)					
Rated operation (100 %)	0015/0022	0037	–	0055/0075	0110
With increased power (VFC, 125 %)	0015	0022	0037	0055/0075	–

For the project planning example, the following was selected: line filter type NF048-503.

Step 25: Select other system components:

Encoder (encoder card)

According to the application data, an absolute value encoder is required. A multi-turn Hiperface encoder was selected. Therefore, the servo inverter requires a suitable encoder card.

For the project planning example, the following was selected: encoder card DEH11B.

Fieldbus

For connecting to the fieldbus system, the following interface was selected: Profibus interface DFP21B.

Step 26: Determine the peak breaking power in section t_3

$$P_{Br\_peak} = \frac{M_{Br\_motor} \times n_{max}}{9550}$$

$$P_{Br\_peak} = \frac{-28.2 \text{ Nm} \times 3820 \text{ min}^{-1}}{9550} = 11.28 \text{ kW}$$

Step 27:
Determine the mean breaking power in section t_3

$$P_{Br\_peak} = \frac{M_{Br\_motor} \times \frac{n_{max}}{2}}{9550}$$

$$P_{Br\_peak} = \frac{-28.2\ \text{Nm} \times \frac{3820\ \text{min}^{-1}}{2}}{9550} = 5.64\ \text{kW}$$

Step 28:
Determine the cyclic duration factor (cdf) of the braking resistor

$$cdf = \frac{t_{Br1} + ... + t_{Brn}}{t_1 + ... + t_n} \times 100\ \%$$

$$cdf = \frac{0.5\ \text{s}}{0.5\ \text{s} + 2\ \text{s} + 0.5\ \text{s} + 1.5\ \text{s}} \times 100\ \% = 11.1\ \%$$

Step 29:
Select and check the braking resistor

Selection of the braking resistor using the MOVIDRIVE® MDX60B/61B system manual: BW018-015.

Requirement: 5.64 $kW_{cdf\ 11\%}$ < 6.7 kW and 11.4 $kW_{cdf\ 6\%}$ > 11.3 kW

→ **requirement fulfilled.**

Step 30:
Check the positioning accuracy

$$\Delta S = \Delta S_{gear} + \Delta S_{encoder} + \Delta S_{mechanics}$$

$$\Delta S_{gear} = \frac{D \times \pi \times \alpha_{gear}}{360°}$$

$$\Delta S_{gear} = \frac{0.25\ \text{m} \times \pi}{360°} \times \frac{6'}{2} = 0.218\ \text{mm}$$

$$\Delta S_{encoder} = \frac{D \times \pi \times 5\ inc}{4096\ inc \times i}$$

$$\Delta S_{encoder} = \frac{0.25\ \text{m} \times \pi \times 5\ \text{inc}}{4096\ \text{inc} \times 10} = 0.095\ \text{mm}$$

$$\Delta S_{mechanics} = 0.3\ \text{mm}$$

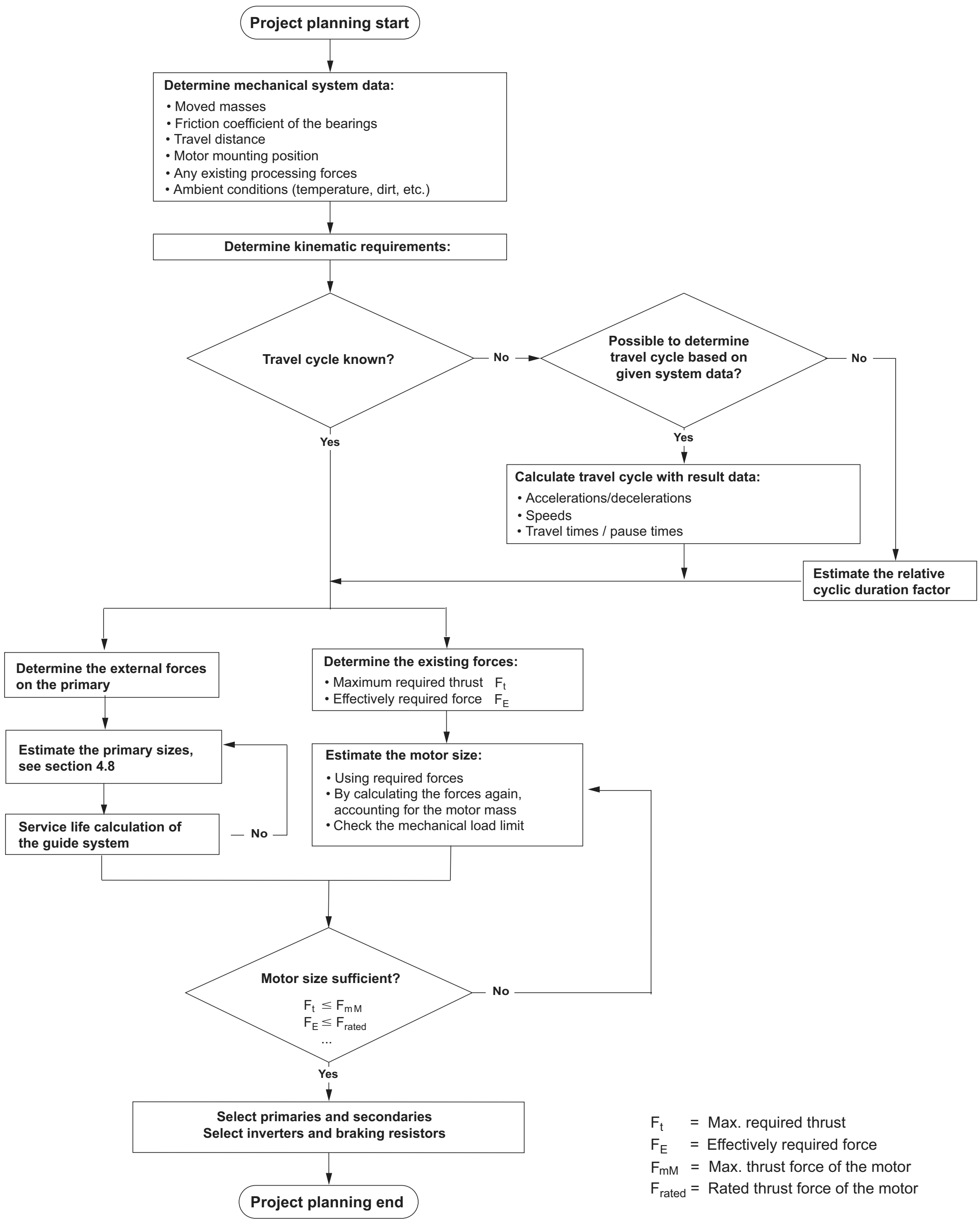
$$\Delta S = 0.218\ \text{mm} + 0.095\ \text{mm} + 0.3\ \text{mm} = 0.613\ \text{mm}$$

Requirement: ΔS < 0.7 mm

→ **requirement fulfilled.**

8.5 Project planning procedure of a linear servo drive

The following flow diagram illustrates the project planning procedure for an SEW SL2 linear drive.



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8.6 Example of project planning for a linear servo drive

Project planning example

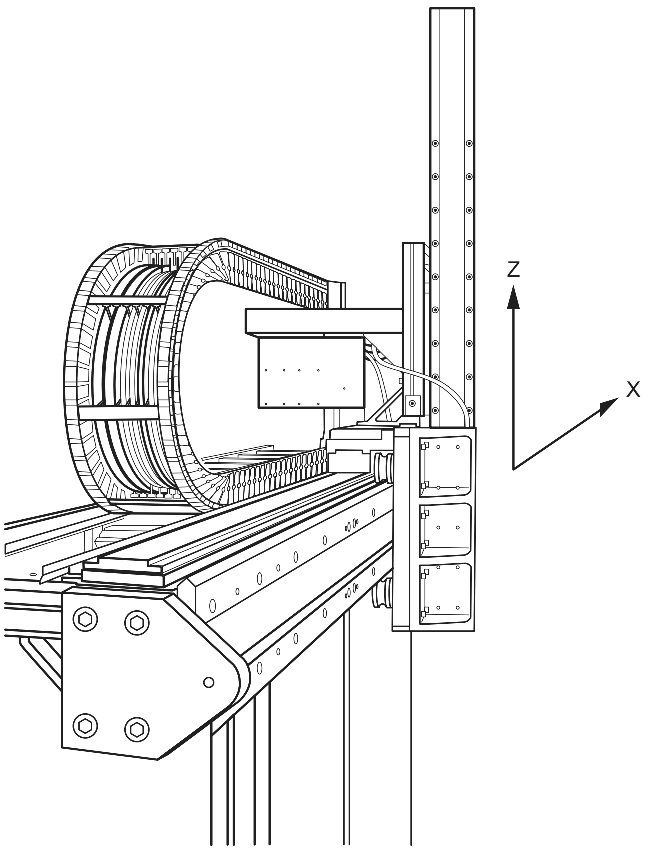

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Fig. 96: High-speed loading gantry

A high-speed loading gantry is to be equipped with SL2 synchronous linear motors.

Reference data:

Horizontal axis (x-axis):

Weight	m_L	= 50 kg + weight of vertical axis
Max. velocity	v_{max}	= 6 m/s
Travel distance	s	= 2 m

Vertical axis (z-axis):

Weight	m_L	= 25 kg
Max. velocity	v_{max}	= 6 m/s
Travel distance	s	= 0.8 m

The cycle time for a product should be kept to a minimum. This requirement results in triangular operation as long as the maximum velocity of 6 m/s is not exceeded by this setup.

Forward [A]	Lower [B]	Lift [C]	Return [D]	Lower [E]	Lift [F]
Approx. 0.5 s	Approx. 0.5 s		Approx. 0.5 s	Approx. 0.5 s	

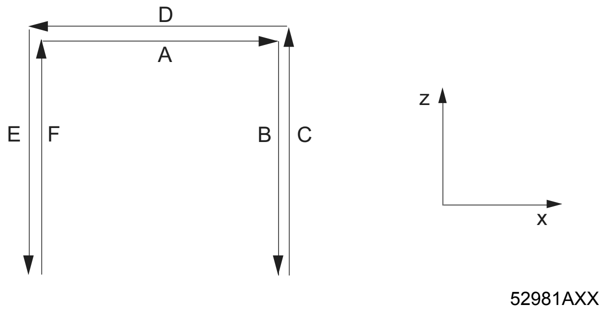

Fig. 97: Travel cycle

This setup results in the following travel diagrams:

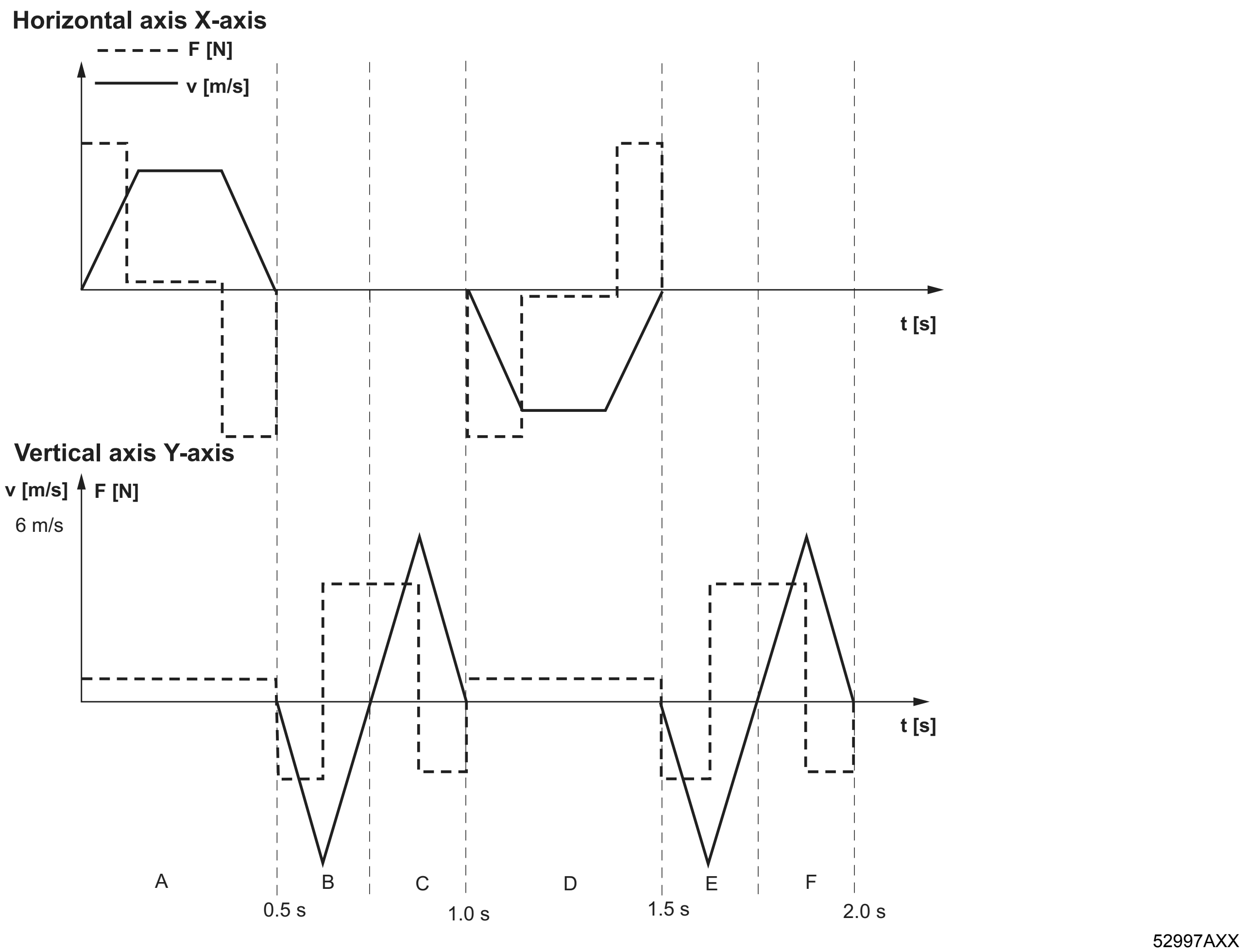

Fig. 98: Travel diagrams

The following project planning example, first the x-axis is calculated and then the z-axis.

Project planning example 1A trolley (x-axis)

Step 1: Determine travel cycle

(Machine zero = left resting position, positive direction of travel: to the right)

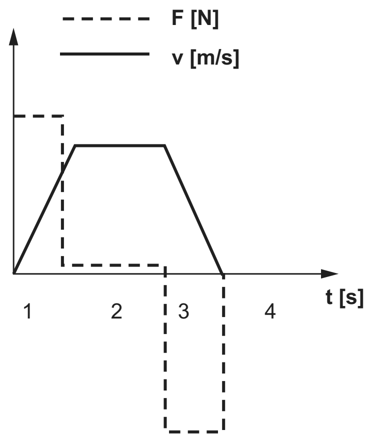

Fig. 99: Sections of the travel cycle

1, 2, 3, 4 = sections of the travel cycle

The travel diagrams show that the drive is to travel 2 m in 0.5 s. Triangular operation requires a maximum velocity v_{max} of:

$$v_{max} = \frac{2 \times s}{t} = \frac{2 \text{ x } 1 \text{ m}}{0.25 \text{ s}} = 8 \text{ m/s}$$

Since $v_{max} > v_{maxMotor}$, it leaves only trapezoidal operation for the x-axis.

Calculation of the required acceleration with estimated trapezoidal operation at 1/3 acceleration, 1/3 constant travel, 1/3 deceleration:

$$a_{max} = \frac{v_{max}}{\frac{1}{3} \times t} = \frac{6 \text{ m/s}}{0.1667 \text{ s}} = 36 \text{ m/s}^2$$

Step 2: Estimate the motor size

The total load of the hoist axis is set at 60 kg to estimate the motor size.

The hoist axis is usually configured first, followed by the travel axis. However, since project planning of a hoist axis is based on the project planning for a travel axis, this order should be reversed and an assumed value taken for the weight of the hoist axis.

These are the results for the trolley:

m_L = 50 kg + 60 kg = 110 kg

$F_{mM} = m_L \times [a_{max} + (g \times \sin \alpha)] \times 1.5$

F_{mM} = 110 kg × 36 m/s^2 × 1.5 = 5940 N

From the motor table, an SL2-P-150ML-060 is selected with:

- F_1 = 6000 N
- v_1 = 6 m/s
- FD = 17000 N
- m_P = 36 kg

Requirement: $F_{mM} \leq F_1$

5940 N ≤ 6000 N → **requirement fulfilled.**

Step 3: Calculate the forces in the individual travel sections and test the dynamic load:

$F_f = (F_W + F_D) \times \mu$

$F_f = [(m_L + m_P) \times g \times \cos\alpha + F_D] \times \mu$

F_f = [(110 kg + 36 kg) × 9.81 m/s^2 + 17000 N] × 0.01 = 184.3 N

Additional process force F_a: none

Dynamic acceleration force:

$F_A = (m_L + m_P) \times a_{max}$

F_A = (110 kg + 36 kg) × 36 m/s² = 5256 N

The formulas for calculating the uniformly accelerated movement result in the following for the individual travel sections:

Step		1	2	3	4
Travel distance	**[m]**	0.5	1	0,5	0
Time	**[s]**	0.167	0.167	0.167	0.5
End velocity	**[m/s]**	6	6	0	0
Acceleration	**[m/s^2]**	36	0	– 36	0
Thrust force	**[N]**	$F_A + F_f$	F_f	$-F_A + F_f$	0
		5440.3	184.3	5071.7	0

These calculations place all operating points within the dynamic limit force characteristic curve and the maximum thrust is

$F_{vmax} = F_A + F_f$ = 2765.7 N

Requirement: $F_{vmax} \leq F_1$

5440.3 N ≤ 6000 N → **requirement fulfilled.**

Step 4: Calculate the effective force, mean velocity and test the thermal load

The effective force and the mean velocity are calculated to determine the thermal load of the motor.

$$F_E = \sqrt{\frac{\sum(F_i^2 \times t_i)}{t}}$$

$$F_E = \sqrt{\frac{(5440.3\ N)^2 \times 0.167\ s + (184.3\ N)^2 \times 0.167 s - (5071.7\ N)^2 \times 0.167\ s}{1\ s}}$$

$F_E = 3040.4$ N

Since v_{max} is always ≤ v_1 during the total travel cycle, the mean velocity is automatically < v_{rated}.

Requirement: $F_E \leq F_{rated}$

3040 N ≤ 3600 N → **requirement fulfilled**, as the thermal operating point is located within the characteristic curve for S1 operation.

Step 5: Select the servo inverter MDx_B

Servo inverter selection using the SL2 synchronous linear motor operating instructions.

When the rated velocity is 6 m/s and F_{max} = 5440.3 N, an MDX61B0300 is selected.

Step 6: Select the braking resistor

The maximum requested power and the mean power with activated braking resistor are determined to select the braking resistor. The braking resistor is active in sections 3; see figure 99.

Maximum power of the braking resistor at the beginning of section 3:

$P_{max} = F_{max} \times v_{max} \times \eta$

P_{max} = 5071.7 N x 6 m/s x 0.9 = 27.4 kW

Travel cycle section 3:

Mean braking power:

$$P_3 = \frac{P_{max}}{2} = 13.7\ kW$$

With cyclic duration factor (cdf) of:

$$cdf = \frac{t_3}{t} = \frac{0.167\ s}{1\ s} = 17\ \%$$

Braking resistor BW012-050 is selected using the MOVIDRIVE® system manual.

Step 7:
Determine the secondaries for the travel distance

The required length of a secondary is calculated as follows:

$s_s \geq s + L_p + (2 \times s_e)$

$s_s \geq 2.0\ \text{m} + 0.72\ \text{m} \geq 2.72\ \text{m}$

The limit switch range S_e was set to 10 mm for each end.

If the drive exceeds the limit switch, the limit switch damper will decelerate it. In this case, the primary must not completely cover the secondary.

The following secondaries are selected:

5 x 512 mm units SL2-S-150-512

and

3 x 64 mm units SL2-S-150-064

Step 8:
Select additional components

You will need additional components for project planning for the entire drive that are not included in the SEW scope of delivery.

These are as follows for the travel axis:

1. Hiperface absolute encoder (Stegmann Lincoder) or incremental encoder
2. Linear guides
3. Cable carrier
4. Motor and encoder cables approved for use with cable carriers
5. Limit switch damper
6. External emergency brake, if necessary

Project planning example 1B hoist (z-axis)

Step 1: Determine travel cycle

(Machine zero = upper resting position, positive direction of travel: to the top)

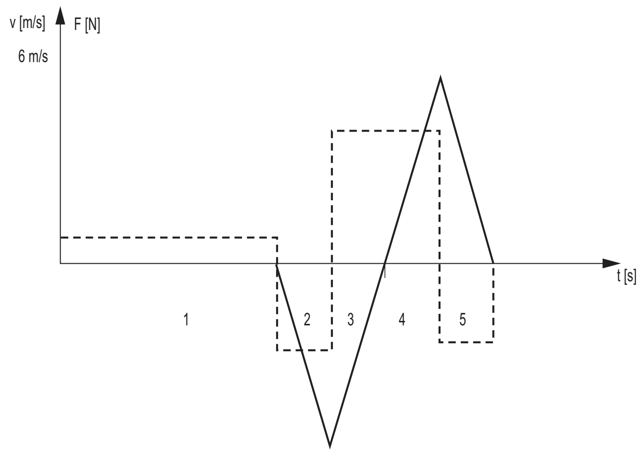

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Fig. 100:Sections of the travel cycle

1, 2, 3, 4, 5 = sections of the travel cycle

Calculation of the necessary acceleration based on triangular operation:

$$a_{max} = \frac{v^2_{max}}{2 \times \frac{s}{2}} = \frac{(6\ \text{m/s})^2}{0.8\ \text{m}} = 45\ \text{m/s}^2$$

$$t = \frac{v_{max}}{a_{max}} = \frac{6\ \text{m/s}}{45\ \text{m/s}^2} = 0.133\ \text{m/s}$$

Step 2: Estimate motor size

$F_{mN} \leq F_1$

$F_{mN} = m_L \times [a_{max} + (g \times \sin 90°)] \times 1.5$

F_{mN} = 25 kg × (45 m/s^2 + 9.81 m/s^2) × 1.5 = 2055 N

From the motor table, an SL2-P-100M-060 is selected with:

- F_1 = 3000 N
- v_1 = 6 m/s
- F_D = 8570 N
- m_P = 18.9 kg

Step 3: Calculate the forces / test the dynamic load

Friction force:

$F_f = (F_W + F_D) \times \mu$

$F_f = [(m_L + m_P) \times g \times \cos 90° + F_D] \times \mu$

F_f = 8570 N × 0.01 = 85.7 N

Weight plus process force (weight + additional weight)

$F_a = (m_L + m_P + m_A) \times g$

F_a = (25 kg + 18.9 kg + 5 kg) × 9.81 m/s² = 480 N

The holding brake of the hoist and the cable carrier with cable and encoder were entered together with 5 kg.

Dynamic acceleration force:

$F_A = (m_L + m_P + m_A) \times a_{max}$

F_A = (25 kg + 18.9 kg + 5 kg) × 45 m/s² = 2200 N

These values result in the following individual motion segments:

Step		**1**	**2**	**3**	**4**	**5**
Travel distance	**[m]**	0	– 0.4	– 0.4	0.4	0.4
Time	**[s]**	0.5	0.133	0.133	0.133	0.133
End velocity	**[m/s]**	0	– 6.0	0	6	0
Acceleration	**[m/s^2]**	0	– 45.0	45.0	45.0	– 45.0
Thrust force	**[N]**	$F_a - F_f$	$-F_A + F_a - F_f$	$F_A + F_a - F_f$	$F_A + F_a + F_f$	$-F_A + F_a + F_f$
		394.3	–1805.7	2594.3	2765.7	–1634.3

These calculations place all operating points within the dynamic limit force characteristic curve and the maximum thrust is

$F_{vmax} = F_A + F_a + F_f$ = 2765.7 N

Requirement: $F_{vmax} \leq F_1$

2765.7 N ≤ 3700 N → **requirement fulfilled.**

Step 4:
Calculate the effective force, mean velocity / Test thermal load

The effective force and the mean velocity are calculated to determine the thermal load of the motor.

$$F_E = \sqrt{\frac{\sum(F_i^2 \times t_i)}{t}}$$

$$F_E = \sqrt{\frac{[(394.3N)^2 \times 0.5s + (1805.7N)^2 \times 0.133s + (2594.3N)^2 \times 0.133s + (2765.7N)^2 \times 0.133s + (1634.3N)^2 \times 0.133s]}{1\ s}}$$

$F_E = 1667\ N$

Since v_{max} is always ≤ v_1 during the total travel cycle, the mean velocity is automatically < v_{rated}.

Requirement: $F_E \leq F_{rated} = 1800\ N$

1667 N ≤ 1800 N → **requirement fulfilled**, as the thermal operating point is located within the characteristic curve for S1 operation.

Step 5:
Select the servo inverter MDx_B

Servo inverter selection using the SL2 synchronous linear motor operating instructions.

Requirement: $F_{vmax} \leq F_{table}$

The following applies to MDX61B0220:

2765.7 N < 3300 N → **requirement fulfilled.**

⚠ For electrically stopping hoists, you must check whether the servo inverter can constantly provide the current for the holding force. This applies even if the entire current flows through an IGBT bridge.

Force constants / reference point

$$k_N = \frac{F_{rated}}{I_{rated}} = \frac{1800\ N}{23.3\ A} = 77.3\ N/A$$

Determining the permitted continuous power:

$$F_{Duration} \leq \frac{I_{rated\_inverter}}{\sqrt{2}} \times k_N$$

$$F_{Duration} \leq \frac{46\ A}{\sqrt{2}} \times 77.3\ N/A$$

$$F_{Duration} \leq 2514\ N$$

Requirement: $F_{Duration} > F_{V\ section\ 1}$

2514 N > 394.3 N → **requirement fulfilled.**

Step 6: Select the braking resistor

The maximum requested power and the mean power with activated braking resistor are determined to select the braking resistor. The braking resistor is active in sections 3 and 5.

Maximum power of the braking resistor at the beginning of section 3 of the travel cycle:

$P_{max} = F_{max} \times v_{max} \times \eta$

P_{max} = 2594.3 N x 6 m/s x 0.9 = 14 kW

Travel cycle section 3:

Mean braking power:

$$P_3 = \frac{P_{max}}{2} = 7 \text{ kW}$$

Cyclic duration factor: t_3 = 0.133 s

Travel cycle section 5:

Mean braking power

$$P_5 = \frac{1}{2} \times F_{max} \times v_{max} \times \eta = 0.5 \times 1634.3 \text{ N} \times 6 \text{ m/s} \times 0.9 = 4.4 \text{ kW}$$

Cyclic duration factor: t_5 = 0.133 s

Travel cycle sections 3 and 5:

Mean power

$$P_{\varnothing} = \frac{(P_3 \times t_3) + (P_5 \times t_5)}{t_3 + t_5} = \frac{(7 \text{ kW} \times 0.133 \text{ s}) + (4.4 \text{ kW} \times 0.133 \text{ s})}{0.266 \text{ s}} = 5.7 \text{ kW}$$

With a cyclic duration factor of :

$$cdf = \frac{t_3 + t_5}{t} = \frac{0.266 \text{ s}}{1 \text{ s}} = 27 \%$$

Braking resistor BW018-035 is selected using the MOVIDRIVE® B system manual.

Step 7:
Determine the secondaries for the travel distance

The required length of a secondary is calculated as follows:

$s_S \geq s + L_P + (2 \times s_E)$

$s_S \geq 0.8 \text{ m} + 0.544 \text{ m} + 0.02 \text{ m} \geq 1.346 \text{ m}$

The limit switch range was set to 10 mm for each end.

If the drive exceeds the limit switch, the limit switch damper will decelerate it. In this case, the primary must not completely cover the secondary.

The following secondaries are selected:

2 x 512 mm units SL2-S-100-512

1 x 256 mm units SL2-S-100-256

1 x 128 mm units SL2-S-100-128

Step 8:
Select additional components

You will need additional components to project the entire drive that are not included in the SEW scope of delivery.

These are as follows for the hoist axis:

1. Hiperface absolute encoder (Stegmann Lincoder)
2. Linear guides
3. Cable carrier
4. Motor and encoder cables approved for use with cable carriers
5. Limit switch damper
6. External service and holding brake

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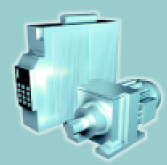
How we're driving the world



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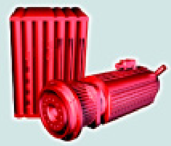

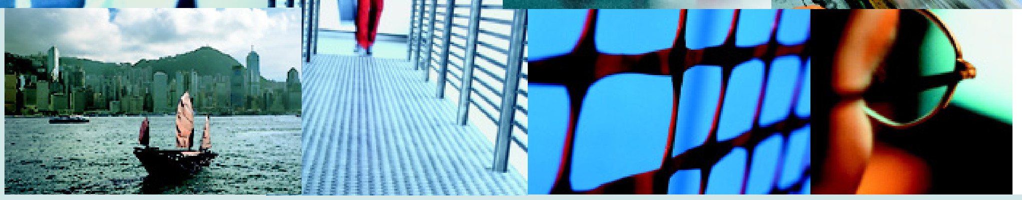

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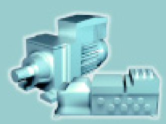

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