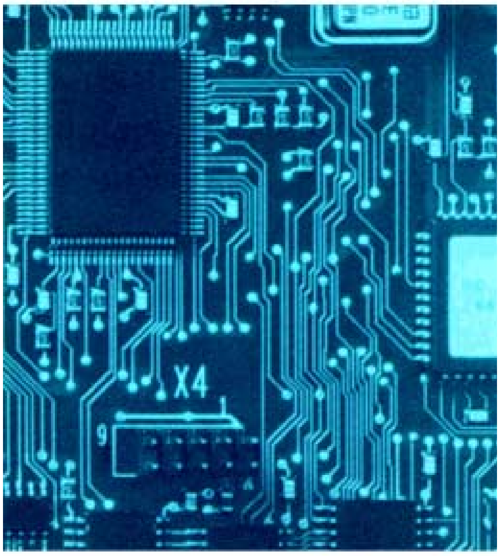

Drive Engineering - Practical Implementation

Volume 7

Servo Drives
Basics, Characteristics, Project planning

Edition 11/96

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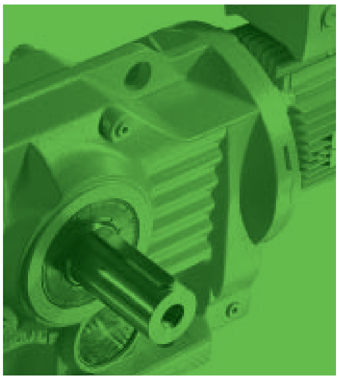
SEW EURODRIVE

The Complete Product Range at a Glance



Geared Motors and Brake Motors

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- Parallel shaft helical gear units / geared motors
- Helical-bevel gear units / geared motors
- Helical-worm gear units / geared motors
- Spiroplan® geared motors
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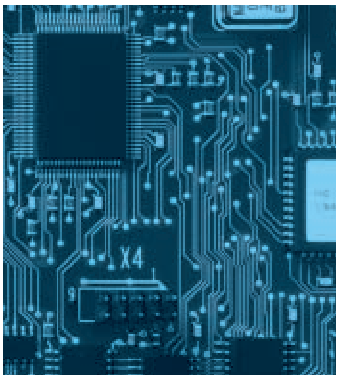
- Brake motors
- Hazardous-duty type AC squirrel-cage motors



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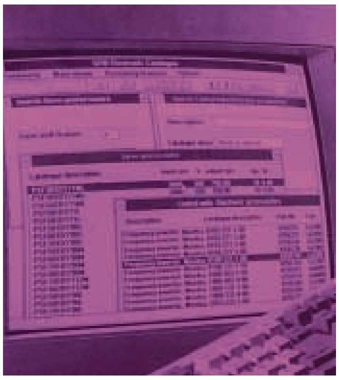

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Appendix

1 Introduction

Developments in the fields of electronics and materials processing have changed the situation in the world of drive technology. Servo technology has to date mainly employed DC permanent-magnet motors. The biggest drawback of AC motors compared to DC motors was their inferior speed control features. Recent developments in the field of electronics, particularly the microcontroller, mean that an appropriate control system can now be included to compensate for this.

These developments have led to a shift in emphasis in drive systems away from DC towards AC motors. This trend towards AC synchronous motors is particularly evident in servo systems, which were previously almost always implemented using DC technology.

New, powerful permanent magnets made of samarium-cobalt and neodymium iron boron can increase the performance of the motor as a result of their high energy density, while at the same time reducing the mass of the motor. As a result, the dynamic properties of the drive are improved and the frame size of the motor reduced.

1.1 Definition of servo technology

Many applications place high demands on modern drive technology with regard to:

- positioning accuracy
- speed accuracy
- speed control range
- torque stability
- overload capability
- dynamic performance

Demands on the dynamic properties of a drive, in other words its time response, arose as a result of ever faster machining processes, increases in machining cycles and the associated production efficiency of machines. The accuracy of a drive is very often instrumental in determining for which applications a drive system can be used.

A modern, dynamic drive system has to be able to satisfy these requirements.

A definition of servo drives

Servo drives are drive systems that show a dynamic and accurate response over a wide speed range and are also capable of coping with overload situations.

The word “servo” comes from the Latin “servus”, which can be translated as servant, slave or helper. In the machine tool sector, servo drives were primarily auxiliary drives. However, this situation has changed, so that nowadays main drives are also implemented using servo technology.

In this volume, we have used the terms “servo drive” and “dynamic drive” to mean one and the same thing. They always refer to AC permanent-field synchronous motors and their associated control systems.

1.2 Development of servo drives

The term “servo drive” suggests some sort of auxiliary drive. This may well have been true 40 years ago in the machine tool industry, when the machines, e.g. lathes, were often still driven by hand. Pneumatic, hydraulic or fixed-speed AC motors were only used where high levels of torque were required. It was the skill of the lathe operator and the manual measurements and checks he carried out that determined how quickly and accurately the workpiece could be machined.

On the other side was the main drive, which used pneumatic, hydraulic or electrical means to achieve a more or less constant and controlled main spindle speed.

1.2.1 Technical development of servo drives

Initially, hydraulic and pneumatic servo drives dominated the market. The DC drive became more important again in the sixties with the advent of silicon semiconductors.

Servo drives were also affected by this development: In view of the requirement for improved dynamic response, development started to go in two separate directions.

The first saw the required reduction in the mass moment of inertia of the motor in the shape of an extremely short, disc-shaped and iron-free rotor. The second concentrated on a long, very thin rotor.

In both instances, the start of the seventies saw permanent magnets being used instead of excitation windings. This meant torque was produced more quickly and resulted in greater efficiency.

What type of control equipment was used? At first, linear amplifiers with power transistors and output voltages up to about 100 V. Later, thyristor converters were used as well and towards the end of the seventies, DC chopper converters based on switching transistors came to the fore.

This compensated to a great extent for the initial low level of efficiency of the electric actuators. The voltage that could be output by the DC motors was nevertheless still only about 200 V as a result of the insufficient blocking voltage of the transistors and the limited voltage between the segments of the commutators.

DC chopper converters had to be connected to the mains via an isolating transformer. At the same time, this transformer isolated the actuator from the mains.

Control of both speed and torque was analogue, with all the associated problems of susceptibility of low signal voltages to interference across the wide speed range typical of servo drives. A DC tachometer was used as feedback unit to measure actual speed.

The development of frequency inverters, initially based on thyristors, later on power transistors, led to the increasing use of low-wear AC squirrel-cage motors and standard motors in the case of drives not requiring such precise control.

The search for brushless motors that could be used in servo drives has been underway since the mid-seventies.

A reversal of the principle of the conventional DC motor appeared to be a promising solution: armature in the stators, field-excitation in the rotors. The brushless DC motor or electronic commutator motor was born.

In principle, this motor is a permanent-field synchronous motor that requires a simple position encoder issuing 6 signals per revolution to determine the position of the rotor.

In addition to electronic commutation and the consequent low rate of wear, this type of drive has the following advantages:

- lower moment of inertia through the use of unwound rotors
- simpler cooling, as power loss occurs in the stators rather than the rotors
- greater efficiency, as there is no loss caused by the excitation winding

Electronic commutation of the current produced by the stator winding occurs every 60° elec. and is controlled by the position encoder. As DC blocks are commutated, this principle is also called block commutation. An additional encoder is required to control speed.

In parallel with these developments, further work has also been carried out to develop the AC squirrel-cage motor as a brushless servo drive. This type of motor is cheap to manufacture and has the additional advantage of being able to operate in the field-weakening range.

Another way towards the brushless drive was the development of what is known as the sinusoidally commutated servo drive:

The principle behind this motor is also the permanent-field synchronous motor, with its advantages as mentioned above. The position encoder for the rotor in this case, however, is a resolver, the output signal from which controls the sinusoidal stator current.

Examples of all three of these principles for brushless servo drives are in use today and have almost completely replaced drives with brushes since the start of the nineties.

The decisive factor in their success has been the progress that has been made in the field of semiconductors. The development of highly integrated, high-speed processor systems and non-volatile memory modules has facilitated the introduction of digital control. Whether or not some functions are required more often or less often in individual systems is no longer significant as far as cost is concerned. Individual software instead of a multiplicity of bits of hardware can be used to implement everything.

The power section in the controller for all three types of brushless systems is basically the same: a frequency inverter that is controlled by the machine rather than the self-controlled inverters used for standard motors. The only functional differences are in the areas of open-loop and closed-loop control.

Developments in power transistors since the early nineties have also made it possible to connect the servo controller directly to the mains voltage without having to use a mains transformer.

1.2.2 Development of the market for servo drives

If the servo drive was initially only to be found in machine tool applications, its potential was very quickly realized in the early seventies as a result of automation in the growth areas of materials handling, industrial robots and automated assembly. In contrast to machine tool applications, the replacement of pneumatic and hydraulic equipment was slower owing to the often very different requirements placed on the drives.

Because of their low mass, the materials handling and robotics industry initially most often employed DC pancake motors, frequently in conjunction with low-backlash planetary gear units or other compact special-purpose gears. The pancake motors were themselves later replaced by brushless motors.

Nowadays, automation is in full swing in all areas of the mechanical engineering sector, the electrical drive is dominant and the mechanics of the machines have been greatly simplified by using modern single drives instead of central drives. As a result, the market for servo drives has expanded. Today, there is hardly any area of engineering in which there are no applications for servo drives. The most important are:

- paper processing
- sheet metal processing
- packaging
- materials handling systems
- wood working
- building materials processing

As servo drives are used very differently in all sectors, not all the applications are highly dynamic. The features of high steady-state or dynamic control precision, the wide speed range, the high surge withstand capability or even just the low weight or small size are often by themselves the decisive purchasing factors.

Thanks to modern digital technology, servo drives are much easier to use than they were a couple of years ago. Digital technology provides a wide range of application-related options, interfaces to all controls (either directly or via a bus system) and the ability to use a PC to commission, optimize and automatically calibrate the drive.

The hydraulic and pneumatic solutions mentioned at the beginning of this section are now confined to niches in the market.

1.3 A comparison of the most common drive systems

If a comparison is to be made of drive systems common with and available from SEW, different factors must be used as a basis for comparison. Comparative criteria must be chosen with great care to avoid comparing apples and oranges.

We shall take a closer look at three principal areas:

- motor characteristics
- basic drive characteristics
- system configuration in a given application

1.3.1 Comparing motor characteristics

The first comparison to be made is that of the motors. We shall compare motors of the same speed and power rating.

Characteristics	**AC asynchronous motor (direct-on-line)**	**DC motor**	**Permanent-field synchronous motor**
Power [kW]	7.5	8.3	7.5
Speed [1/min]	2900	3200	3000
Type / Size	DFV 132 M2	GFVN 160 M	DFY 112 ML
Enclosure	IP 54	IP 44	IP 65
Cooling	fan-cooled	fan-cooled	self-cooled via surface
Length [mm]	400	625	390
Total weight [kg]	66	105	38.6
Weight of rotor [kg]	17	29	8.2
J_{mot} $[10^{-4}\ kgm^2]$	280	496	87.4
Rated torque [Nm]	24.7	24.7	24
Maximum torque M_{max}	$2.6 \cdot M_N$ / $1.8 \cdot M_N$ 1)	$1.6 \cdot M_N$	$3 \cdot M_N$
Max. angular acceleration α $[1/s^2]$ 2)	1588	797	8238
Max. dynamic performance [%] 4) (servo motor = 100%)	20	10	100
Acceleration time t_H 3) [ms]	191	420	38

1) Given are the pull-out torque and the mean acceleration torque M_H, which is used for calculation.

2) Max. angular acceleration $\alpha = \frac{M_{max}}{J_{mot}}$

3) $t_H = \frac{J_{mot} \cdot n_{mot}}{9.55 \cdot M_{max}}$

4) $\frac{\alpha}{\alpha_{servo}} \cdot 100\%$

Some typical motor characteristics are evident just by looking at the table. Shaded motor characteristics shall be dealt with in greater detail.

Weight of motors and rotors

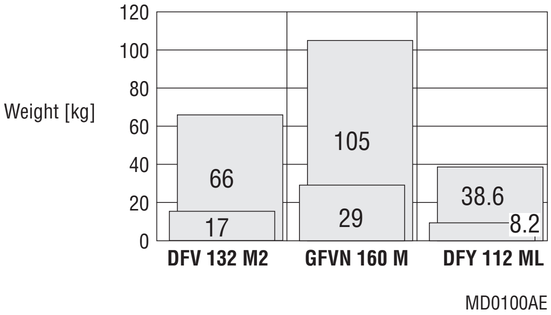

Fig. 1: Weight of motors and rotors

Figure 1 shows the weight of the different motors in comparison. It is obvious that the synchronous motor has by far the lowest weight. In particular in systems where the drive is traveling together with the system a low motor weight is of major advantage.

The power/weight ratio of the motors compares as follows:

- asynchronous motor: 8.8 kg/kW
- DC motor: 12.7 kg/kW
- synchronous motor: 5.2 kg/kW

Motor moment of inertia

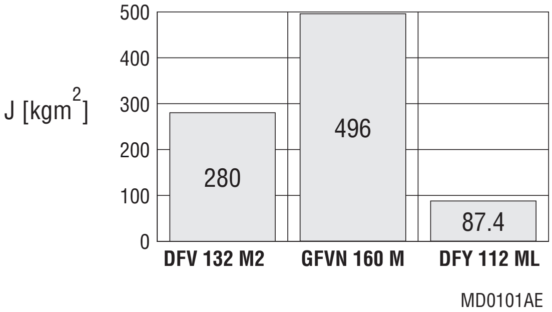

Fig. 2: Motor moment of inertia

Figure 2 compares the mass moment of inertia of the motors. Again, the difference between the servo motor and the DC motor in particular is striking. A small mass moment of inertia of the motor is of advantage particularly in terms of dynamic performance. It is unfavourable however when larger external masses are to be moved.

Dynamic performance

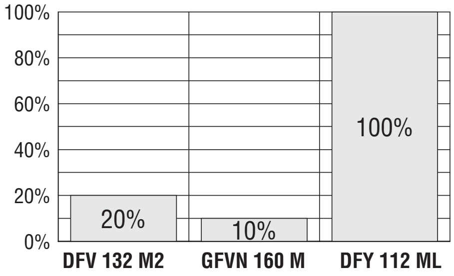

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Fig. 3: Dynamic performance

Figure 3 clearly shows the lead the synchronous motor has over the other systems in terms of dynamic performance.

Acceleration time without load

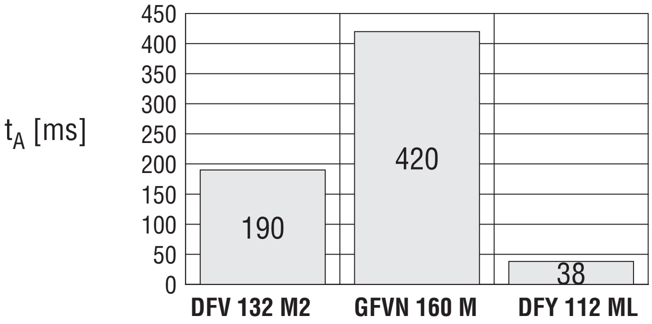

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Fig. 4: Acceleration time without load

With its maximum motor torque M_{max} and its low mass moment of inertia J_{mot} the synchronous motor has a very short acceleration time when not loaded which highly recommends it for dynamic applications.

1.3.2 A comparison of basic drive characteristics

Controlled drives have special characteristics which influence drive selection.

Characteristics	**DC motor**	**Asynchr. motor, frequency inverter controlled (open loop V/f)**	**Asynchr. motor, frequency inverter controlled (closed loop V/f)**	**Synchronous motor**
Control range R	100 (300):1	10 (20):1	100:1	300 (10,000):1
Overload [%] of M / M_N	150 ... 200	150	> $M_{pull\text{-}out}$[1]	300
t_a [%] closed loop controlled (synchronous = 100%)	500	450 ... 500	300 ... 400	100
Forced cooling fan for wide control range R	yes	yes	yes	no
Static torque	to a limited extent	no	to a limited extent	yes
Maintenance (motor)	extensive	little	little	little
Repair (motor)	medium	easy	easy	difficult
Third-party motor on DC controller [2]	yes	yes	yes	possible
Stock level requirements	extensive	minor	minor (feedback system)	extensive
Operation with large external masses	excellent	good	good	difficult because of small J_{mot}
Emergency stop via mech. motor brake[3]	good	good	good	good[4]
4-Q operation with	mains energy feedback	brake chopper / braking resistor	brake chopper / braking resistor	mains energy feedback or brake chopper/ braking resistor
Positioning performance and repeat accuracy	depends on tachogenerator and periphery (between servo and asynchronous motor with speed control)	clearly not as good as that of the asynchronous motor with closed-loop speed control (depends on peripheral conditions (PLC, brake, etc.))	positioning accuracy to approx. ± 50 angular minutes	positioning accuracy to approx. ± 5 angular minutes

1) When the motor is fed from the frequency inverter with a speed control option, appropriate selection of the frequency inverter will provide a motor torque of 300% M_N and more.

2) Third-party motors in current-controlled systems require specific knowledge of the motor characteristics to properly adjust the current controller. Furthermore knowledge is required of the technical details of the feedback and the evaluation systems, the commutation method, etc. Therefore, it is common practice, in particular in servo technology to purchase all components from one manufacturer (one-stop-solution).

3) Taking into account the maximum permissible braking work, SEW DFY brake motors can handle several emergency stop braking operations.

4) In the synchronous motor the mechanical brake is a mere emergency and holding brake.

When selecting a drive component a drive's enclosure, maintenance/maintenance intervals, ambient conditions (which are essential for cooling, frame size, weight, dust generation, etc.) must be taken into consideration.

1.3.3 A comparison of different system configurations in a given application

Having concluded all initial observations, the next step is to configure different systems and to compare the systems' performance in a given application. All systems compared were chosen with the same power rating and output speed as a basis for comparison.

Load data: m = 1000 kg; v_{max} = 1.5 m/s

Characteristics	**Asynchronous motor**			**DC motor**	**Synchronous motor**
	ASM direct-on-line	FI with V/f	FI with n controller		
Type	DV 132S4 1400 1/min	DV 132S4 1400 1/min	DV 132S4 1400 1/min	GVN132S 3200 1/min	DFY 112M 3000 1/min
Power	5.5 kW	5.5 kW	5.5 kW	5.3 kW	17.5 Nm ≙5.5 kW
Gear unit	R82 i = 14.69	R82 i = 14.69	R82 i = 14.69	R73 i = 33.87	R82 i = 31.78
Controller rating/ current	N/A	MC 31B 055 5.5 kW	MC 31B 075 7.5 kW	MR 315 15 A	MAS 51A-030 30 A
M_H	2.4 M_N	1.3 M_N	2.0 M_N	1.5 M_N	3 M_0
Max. acceleration time **Max. acceleration**	230 ms 6.7 m/s^2	450 ms 3.5 m/s^2	300 ms 5.3 m/s^2	620 ms 2.43 m/s^2	200 ms 7.45 m/s^2
J_{ext}/J_{mot}	5.4	5.4	5.4	1.0	3.4
Brakes	mechanical braking from full speed	dynamic braking then mechanical brake	dynamic braking then hold control / mechanical brake	dynamic braking then mechanical brake	dynamic braking then hold control / mechanical brake
Total stopping distance (approx.)	150 mm	300 mm	190 mm	380 mm	125 mm
Theoretical stopping accuracy[1]	18 mm	0.4 mm	0.12 mm	0.12 mm	0.05 mm
Practical stopping accuracy	approx. 25 mm	approx. 3 mm	approx. 1 mm	approx. 1 mm	approx. 0.5 mm

1) Not included are the response times of PLC, frequency inverter and contactor, the brake release reaction times and the gear unit backlash.

Brake reaction times for switch-off in the AC and DC circuits are considered.

1.4 Advantages and disadvantages of a servo drive

Advantages:

- excellent speed holding
- excellent dynamic performance
- wide speed range
- high positioning accuracy
- static torque (zero speed)
- high overload capability (3 · M_0)

Disadvantages:

- relatively high system cost

1.5 Components of a servo system

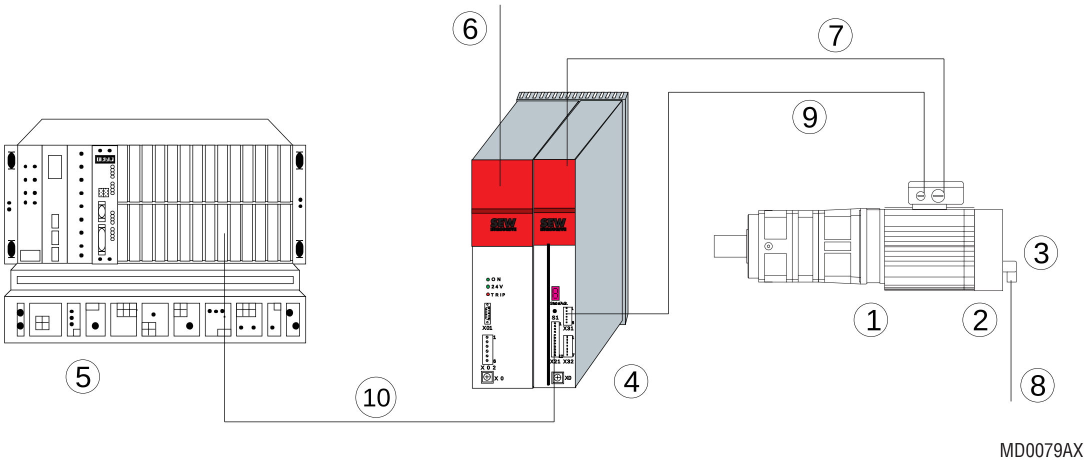

Fig. 5: Components of a dynamic drive

Figure 5 shows the components of a servo system. Essentially, the following components are required:

1 Motor with/without gear unit
2 Feedback system
3 Brake (optional)
4 Servo controller
5 Control system for external setpoint input
6 Power cable
7 Motor cable
8 Brake cable
9 Resolver leads
10 Control leads

The following sections will deal with these components in greater detail.

1.6 Overview of common servo motors

Until a few years ago, servo drives were implemented in DC technology with brushless permanent-field motors with either thyristor or transistor power controllers.

Brushless AC permanent-field synchronous motors, as produced, among others, by SEW are increasingly used nowadays. Their advantages over DC drives are:

- better price/performance ratio
- better performance/weight ratio
- longer service life
- high thermal load rating

Servo motors can be divided into several groups:

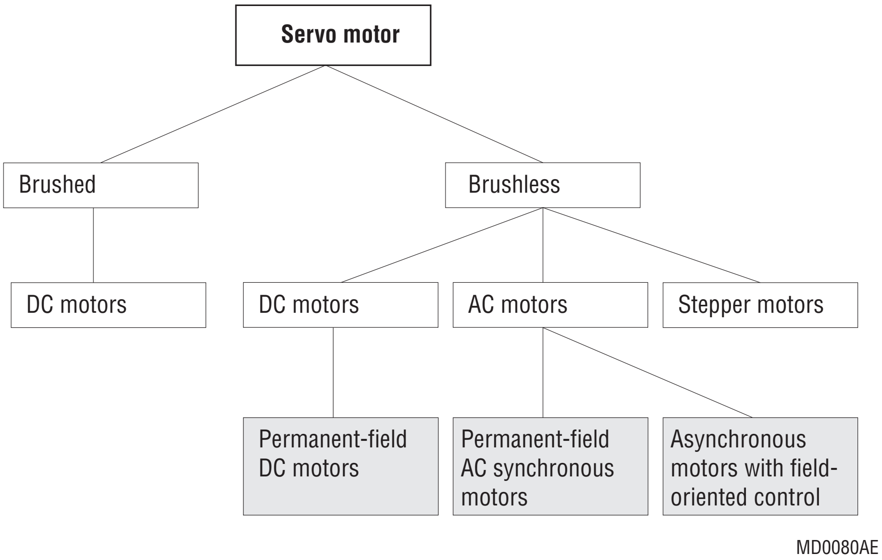

Fig. 6: Classification of servo motors

The distinguishing features are in the design of the motor, in the controller design and the type of feedback system used.

The three major systems are briefly explained here:

- asynchronous motor with squirrel-cage rotor and field-oriented control (Sec. 1.6.1)
- permanent-field synchronous motor (with block-type commutation) / brushless DC (Sec. 1.6.2.1)
- permanent-field synchronous motor (with sinusoidal commutation) / brushless AC (Sec. 1.6.2.2)

1.6.1 Asynchronous motor with squirrel-cage rotor and field-oriented control

The asynchronous motor with squirrel-cage rotor and field-oriented control is also termed an AC servo motor. In its basic structure and mode of operation this motor corresponds to the well-known three-phase asynchronous motor with squirrel-cage rotor.

As servo motors, asynchronous motors are designed with low-inertia, low-leakage and low-slip rotors and are operated with a special control which ensures that stator and rotor flux are always perpendicular to one another. This allows the asynchronous motor to be operated at almost breakdown torque whenever dynamic responses are required, making it highly suitable for high-dynamic applications.

The disadvantage of this motor (compared with the permanent-field machine) is its lower efficiency and somewhat greater unit volume in relation to the torque. Current-dependent losses occur in the rotor which do not occur with a permanent-field rotor. Because of the higher losses (efficiency η) and the magnetizing requirements (power factor $\cos\varphi$) of the asynchronous machine, it requires an inverter output higher by the inverse ratio of $\eta \cos\varphi$

$$\frac{1}{\eta \cdot \cos\varphi}$$

Further heat dissipation measures have to be taken especially in the range of lower speeds. These motors are then usually provided with forced cooling fans or the speed control range or torque is reduced.

The costs compared with other systems are higher due to the complexity of the signal processing involved in high-dynamic applications. It is mainly the high-resolution encoder and the fast and efficient microprocessors which are responsible for that. The processor must continually calculate the stator currents from the rotor position and the required torque-producing and magnetizing components.

Previously these drives were generally used as high-output main drives in the machine tool industry. However, the use of these drives can be expected to increase because electronic components are becoming cheaper and the motors can be produced more economically.

The torque-speed characteristic shows the curve with

1 continuous torque
2 maximum torque
3 characteristic of the standard asynchronous motor in comparison

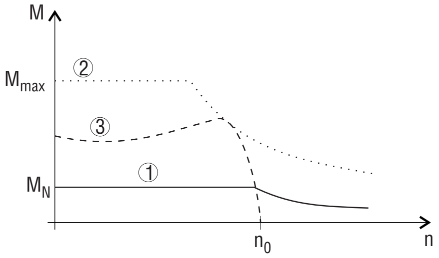

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Fig. 7: Torque-speed characteristic

Characteristic **2** shows the envelope which depends on the DC link voltage of the inverter and its current capacity.

1.6.2 Permanent-field synchronous motor

The permanent-field synchronous motor, sometimes also referred to as electronically-commutated motor or brushless DC motor is currently the motor which best satisfies the requirements made of a servo system. The stator can be compared directly with that of the asynchronous motor. The laminated rotor has adhesively attached magnets which provide the constant magnetic field. The motors are normally enclosed (minimum IP 54) and fan-cooled.

The motor can be operated with different current injection methods, block-type and sinusoidal commutation techniques having been accepted in this case. The difference lies in the induced current flow and in the type and implementation of the feedback systems.

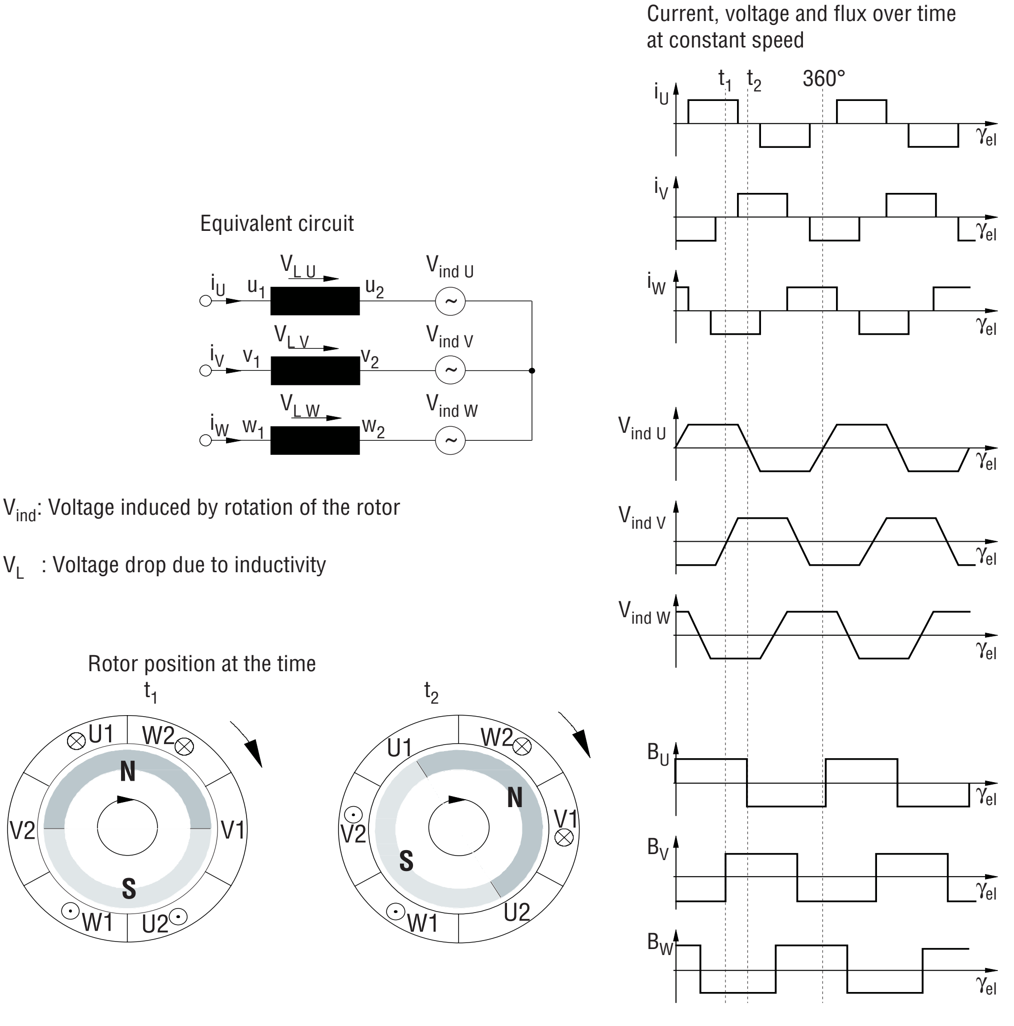
1.6.2.1 Permanent-field synchronous motor (with block-type commutation) / Brushless DC

The AC permanent-field synchronous motor with block-type commutation as described in the following is often called the brushless DC motor.

In block-type commutation, the current controller and power output stages are controlled by a rotor position encoder (RLG). These could consist of Hall sensors, photoelectric sensors, or something the like.

A major advantage of the block-type commutation is simple generation of position signals and their conversion to control signals for the current.

The curves of the individual characteristic parameters are shown in the figures below.



Current, voltage and flux over time at constant speed

Equivalent circuit

V_{ind}: Voltage induced by rotation of the rotor

V_L : Voltage drop due to inductivity

Rotor position at the time

Fig. 8: Block-type commutation

Block-type currents are injected into the motor windings as a result of which trapezoidal voltages are induced in the motor. The design then produces rectangular distribution of the air-gap flux density. This results in constant torque development.

Two adjacent phases are always fed with current in block commutation.

The rotor position encoder is used to detect the rotor position, and brushless tachogenerators to detect the speed.

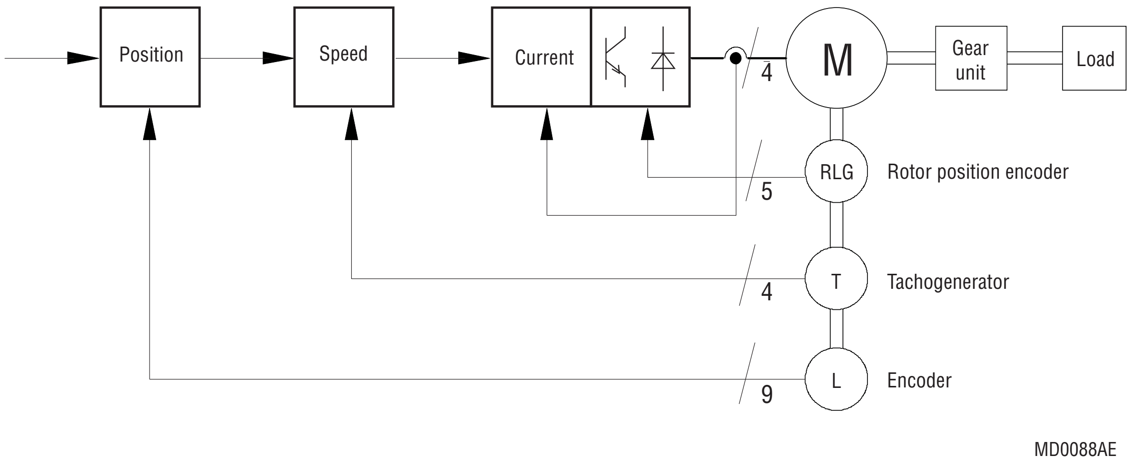


Fig. 9: Control structure of the block-commutated motor with encoder

Figure 9 shows the components of a control loop in the block-commutated motor. It shows clearly that a dedicated actual-value encoder plus wiring is required for each controlled variable.

1.6.2.2 Permanent-field synchronous motor (with sinusoidal commutation) / Brushless AC

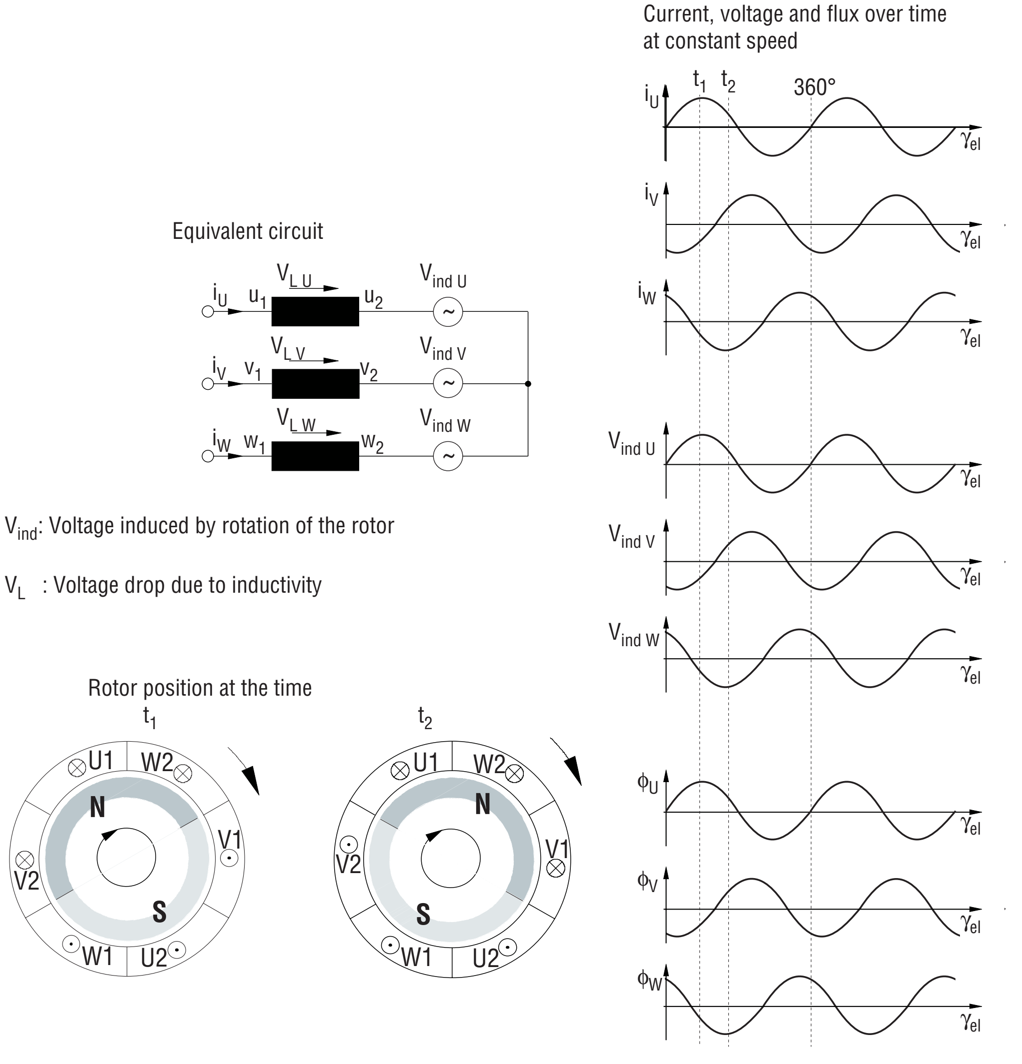


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Fig. 10: Sinusoidal commutation

Basically, the commutation sequence takes place on the same principle as in block-type commutation. The differences are that all the three phases are now simultaneously fed with current, and that the current, the induced voltage and the flux are sinusoidal. This means that torque and speed stability are achieved, even at low speeds. Additional measures in the mechanical design of the motor aid this.

The sinusoidal-fed motors are normally equipped with resolvers as feedback systems. Resolvers are certainly more complex in their evaluation, however offer higher resolution because the evaluation is digital, and save one feedback system, in particular when there is a position control superimposed, thereby reducing the wiring requirements as well.

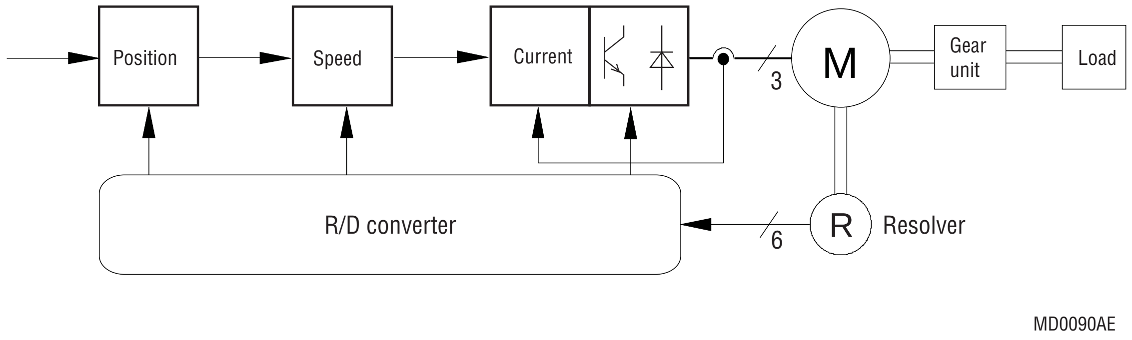

Fig. 11: Control structure of a sinusoidally commutated motor

Motor control of a sinusoidal-fed permanent-field synchronous motor is described in detail in Sec. 4.

1.7 Feedback systems

An feedback system is used to detect specific drive data, including:

- speed
- load angle (position within one revolution)
- machine position (position over several revolutions)

1.7.1 Overview of the most common feedback systems

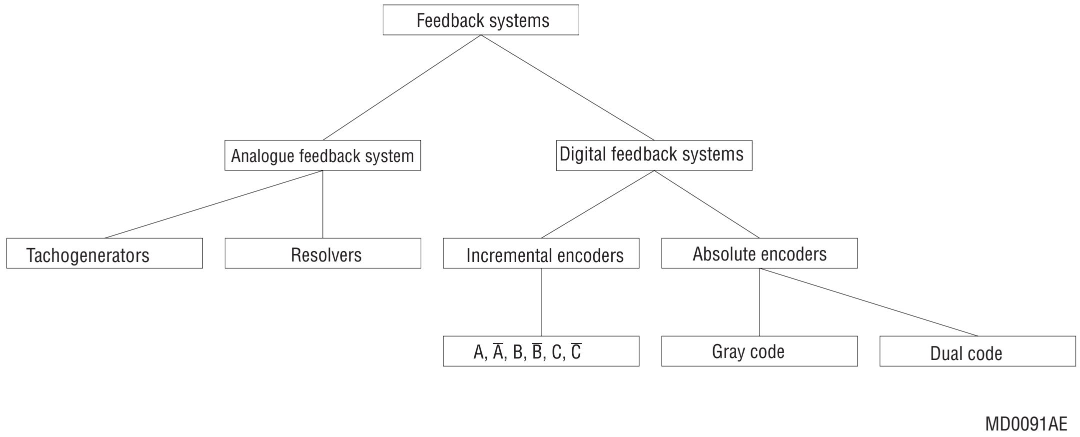

Fig. 12: Overview of feedback systems

The different feedback systems supply the following data:

Feedback system	Supplied data		
	Rotor phase angle	**Machine position**	**Speed**
Absolute encoder singleturn	X	(X)	(X)
Absolute encoder multiturn	X	X	(X)
Incremental encoder	(X)	(X)	(X)
Resolver with R/D converter	X	(X)	X
Tachogenerator			X

X can be evaluated directly, (X) available with additional evaluation

An important criterion when selecting a feedback system is its ruggedness. Since the feedback system is mounted directly on the motor, it must be able to handle higher temperatures and vibration. Another important factor is the feedback system's RF noise immunity.

1.7.2 Advantages and disadvantages of the major feedback systems

Feedback system	Advantage	**Disadvantage**
Incremental encoder	● relatively rugged designs available ● large selection of resolutions, mounting types, interfaces	● position data is lost in the case of a power failure
Absolute encoder	● position data is still available after a power failure ● clear assignment of position and output value ● very high resolution available	● high cost
Resolver	● rugged design ● insensitive to vibrations and higher temperature ● low wiring requirement ● can be fitted in motor ● economizes on additional feedback systems	● more complex evaluation

When weighing the pros and cons of the different feedback systems the resolver recommends itself as highly suitable for use with the servo motor.

2 The permanent-field synchronous motor

2.1 Design and method of operation

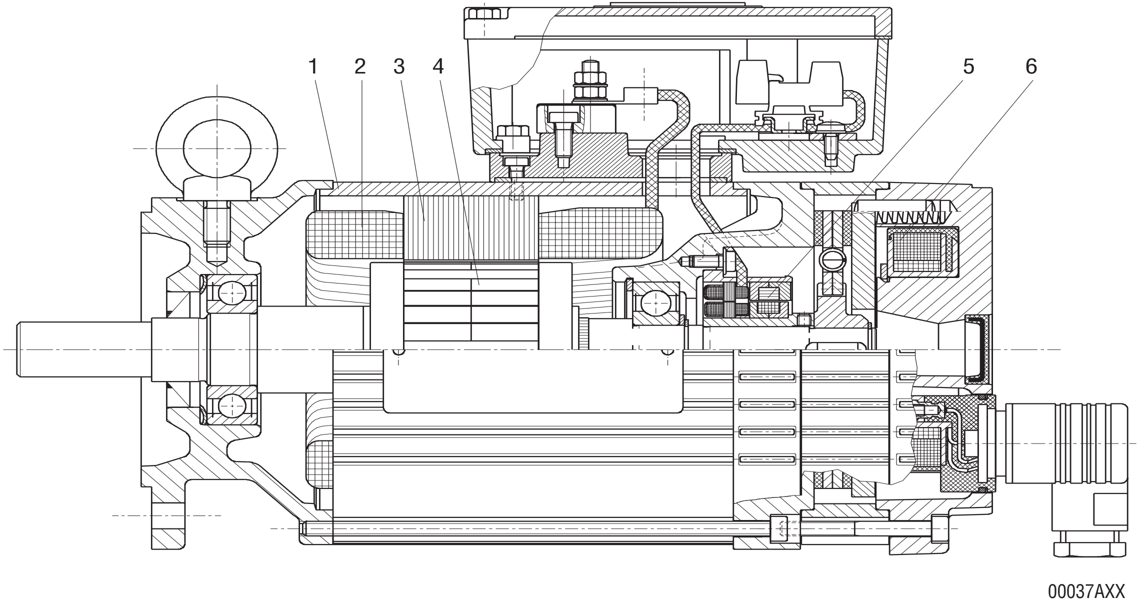

Fig. 13: Sectional view of a permanent-field synchronous motor

Explanation:

1. Stator housing	4. Rotor with permanent magnets
2. Stator winding	5. Resolver
3. Laminated stator core	6. Brake

Synchronous motors are polyphase machines in which the stator rotating field and the rotor rotating field run synchronously.

A rotating field is generated by the spatial arrangement of the stator coils and the chronological phase sequence of the input current.

The speed of the rotating field n_d is derived as follows:

$$n_d = \frac{f \cdot 60}{p}$$

where: f = frequency of the applied voltage
p = stator pole pair number

SEW synchronous motors are always 6-pole motors (p = 3).

f [Hz]	100	150	225
n_d [min^{-1}]	2000	3000	4500

The speed as a function of the frequency when p = 3.

SEW permanent-field synchronous motors are designed as 6-pole motors since the use of 6-pole motors makes for minimal iron losses at 3000 min^{-1} (150Hz) and at the same time ensures good torque stability with low magnet requirement.

SEW synchronous motors are, fundamentally, star-connected.

As with the asynchronous motor, the stator consists of the housing, the laminated core assembly and the stator winding. The rotor consists of a shaft, rotor laminates and adhesively attached permanent magnets. To improve the dynamics of the motor the laminates of the rotor are not solid but with cutouts (see Fig. 14). This reduces the rotor’s moment of inertia and, thus, its acceleration time.

The permanent magnets used are of the rare-earth material neodymium-iron-boron. Magnets in this material have particularly good magnetic properties compared with the previously used ferrite magnets and can produce higher torques.

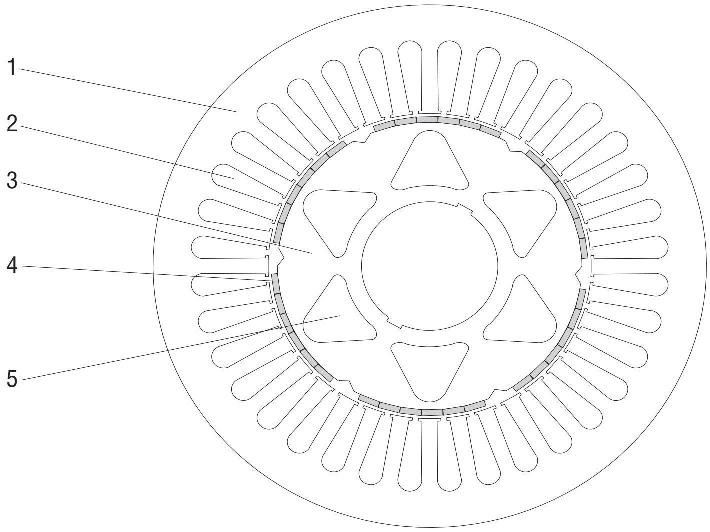

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Fig. 14: Sectional view of stator and rotor

Explanation:
1. Stator core assembly
2. Winding slots
3. Rotor laminates
4. Permanent magnet
5. Cutouts

2.1.1 Function of the AC permanent-field synchronous motor

If the motor is connected to a suitable controller, a rotating field - the so-called stator rotating field - is produced in the windings of the stator. This rotating field operates on the rotor and exerts a force on it. Because of the magnetic coupling between stator and rotor, the rotor is accelerated into this field and runs at the same angular velocity, i.e. synchronously.

If the motor is loaded, a lag of the rotor rotating field in relation to the stator rotating field is produced. The poles of the rotor lag to those of the stator rotating field by a certain angle, the load angle α. The greater the load angle, the more the torque increases. If the load angle is precisely 90°, i.e. the poles of the rotor lie precisely between two stator poles, then the force operating on the rotor is at its maximum. The stator pole leading the rotor pole “pulls” the rotor and the lagging stator pole “pushes” it, producing the described effect. If the load angle is further increased, i.e. the motor is overloaded, the torque decreases again, motor operation becomes unstable, the motor stalls and comes to a standstill.

Where: $M = f(V, I, \sin \alpha)$

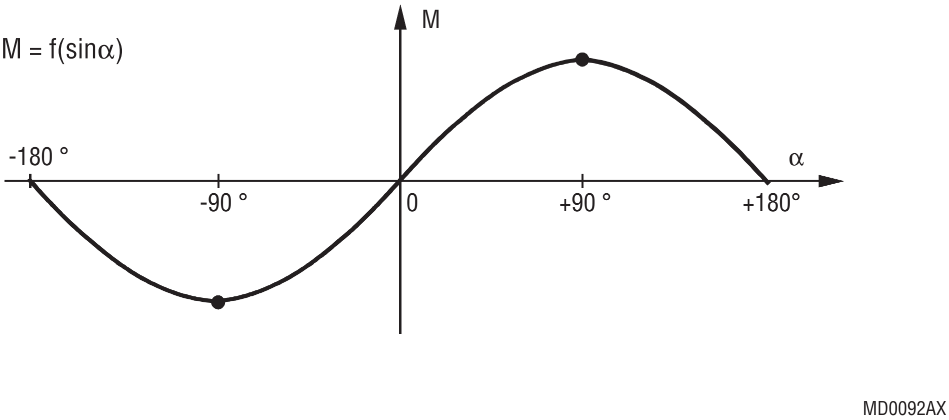


Fig. 15: The torque as a function of the load angle

2.1.2 Motor control

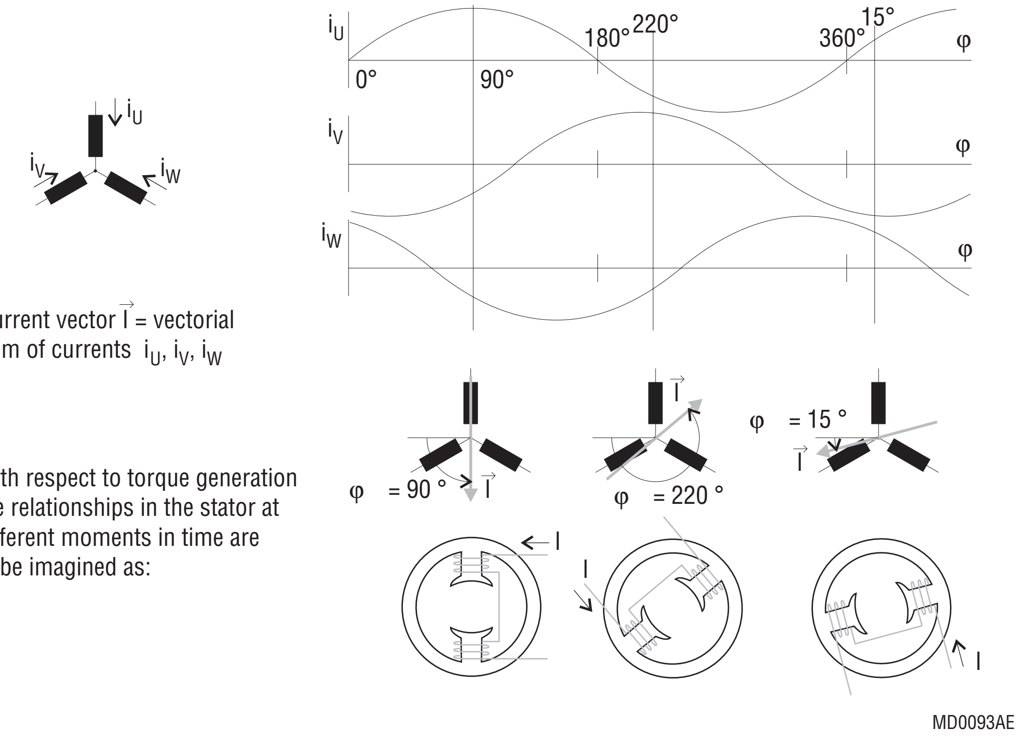
To be able to operate a synchronous motor with maximum possible torque, it must be ensured that the load angle α is 90°. This means that the stator field must always lead by 90° when the drive is motoring and lag by 90° when it is regenerating. The motor control calculates the three phase currents of the motor from a given torque and reads out the current setpoints from a table.

For this purpose the rotor position is sensed with the position encoder. 90° is added or subtracted to or from the value of the position angle, according to direction of rotation and direction of torque, and the associated currents are then calculated.

The appropriate position of the stator rotating field is determined for each rotor position, i.e. the rotor determines the magnitude and direction of the stator field. Thus the rotor “rotates” the stator field.

The load angle α mentioned in this context is always the electrical angle. In a six-pole motor 90° electrical corresponds to 30° mechanical.

2.1.3 Current relationships in the stator



Current vector $\vec{I}$ = vectorial sum of currents i_U, i_V, i_W

With respect to torque generation the relationships in the stator at different moments in time are to be imagined as:

Fig. 16: Current vectors

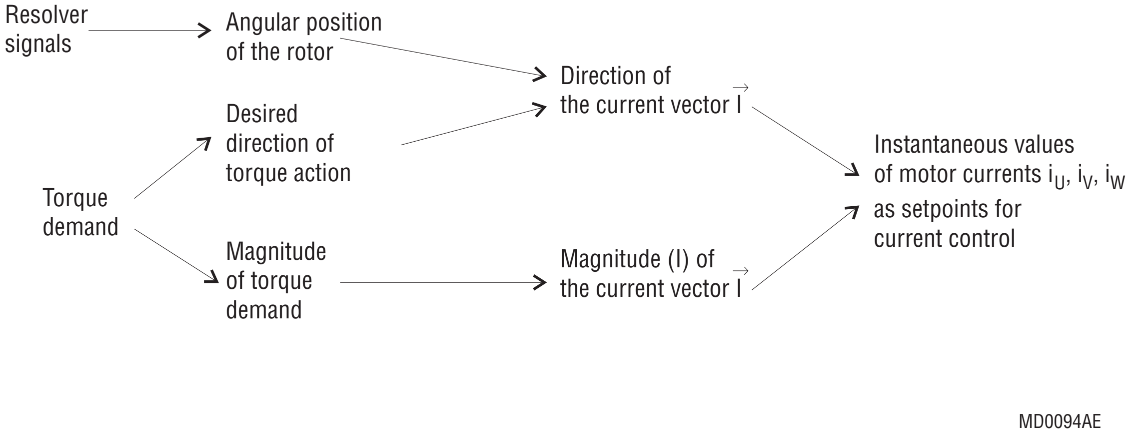


Fig. 17: Generation of current instantaneous values

2.2 Speed-torque characteristic

Three limits can be seen in the speed-torque characteristic of a DFY motor. These must be considered when configuring a drive.

1) The maximum torque of a motor is limited, among other factors, by the load rating of the permanent magnets. If a motor is too heavily loaded and the current increases to an excessive value, the magnets become demagnetized and the motor “loses its torque”.

No demagnetization can occur with correct selection and matching of motor and controller.

2) Further attention should be paid to the limitations in torque in the upper speed curve, which are caused by the voltage. “Voltage” here refers to the voltage which is present on the motor terminals. It depends on the DC link voltage, the mains supply voltage, and the voltage drop in the cables. The reason for the decrease in torque is that the maximum current can no longer be injected into the motor due to the back e.m.f. (voltage induced in the motor). The motor can no longer attain the maximum torque.

3) A further limitation is the thermal load of the motor, which must additionally be calculated in the design. Rms torque is calculated in this case, and it must be smaller than the static torque M_0. If the thermal limit rating is exceeded, the magnets will become demagnetized.

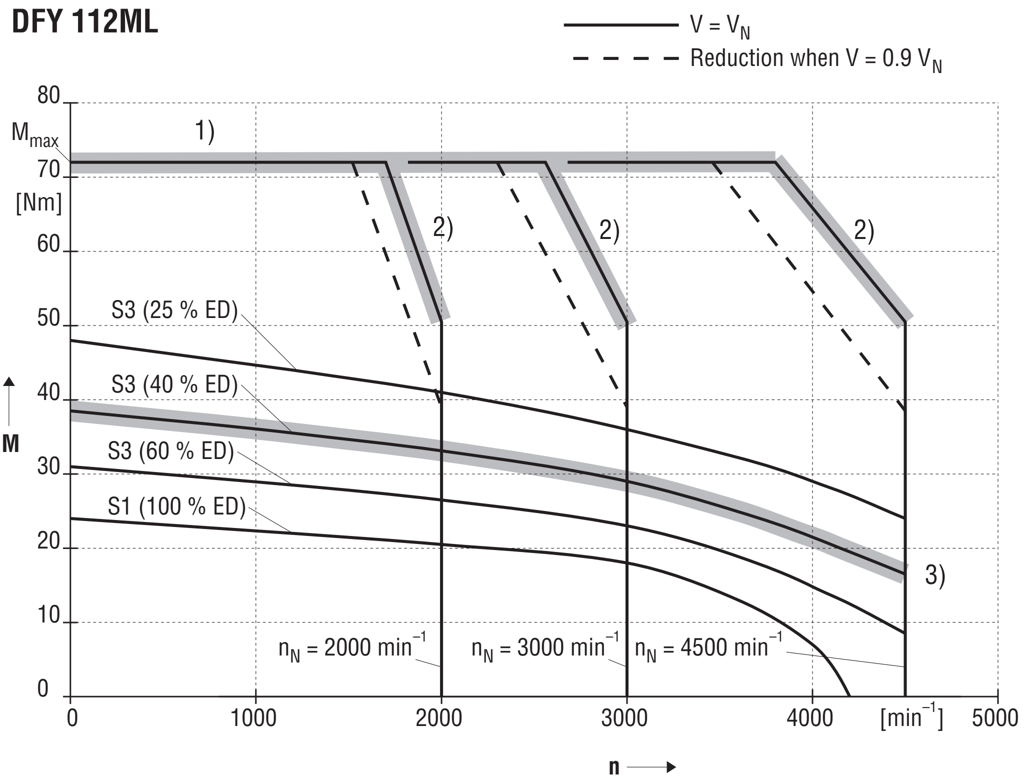


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Fig.18: Speed-torque characteristic of a servo motor (ED = c.d.f. or cyclic duration factor)

2.3 Electromechanic emergency and holding brake

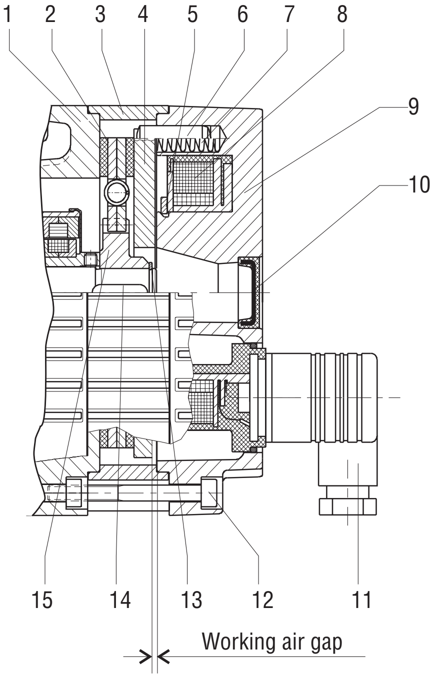
The brake which is used in the larger frame-size servo motors is based, in its mechanical layout, on the service brake of the asynchronous motor. However, in servo technology this brake is only required as emergency and holding brake, as braking and holding are performed electrically. Even though the brake used in SEW synchronous motors is only employed as emergency and holding brake, it can still produce a high holding torque ($3 \cdot M_0$) and do considerable braking work. This makes synchronous brake motors by SEW particularly suitable for hoisting applications.

The brake is normally only used in the event of:

- longer stationary periods (reducing the thermal load on the motor)
- emergency stops

The optional disc brake is fully integrated in the motor. Removal and installation can be performed on site, without interfering with the motor.

The brake has a separate plug connector for its independent electrical supply. Standard brake supply voltages are 230 V_{AC}, 400 V_{AC} and 24 V_{DC}.



Explanations:

1. Brake end shield
2. Brake disc compete
3. Spacer collar
4. Pressure plate
5. Circlip/snap ring
6. Parallel pin
7. Brake spring
8. Brake coil complete
9. Coil body
10. Closing cap
11. Right-angle connector
12. Cheese head screw
13. Circlip/snap ring
14. Key
15. Carrier

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Fig.19: Sectional view of the brake

The brake is a DC excited electromagnetic disc brake which is released (opened) electrically, i.e. when power is supplied, and brakes by spring force. The system satisfies basic safety requirements. The brake is applied automatically if the voltage is removed or in case of a voltage failure.

The disc brake operates on the well-proven two-coil principle. The brake rectifier or brake control units initially only energize the accelerator coil. As soon as the brake is released, the system switches over to the holding coil electronically.

Minimum wear together with maximum service life and high switching capacity are the outstanding features of this brake system.

The I^2R losses are reduced as much as possible in continually-released operation, so that thermal load on the brake is very small.

The braking torque is determined by the type and number of brake springs. Brakes with higher braking torque (up to $3 \cdot M_0$) are preferred for hoisting applications.

Brake rectifiers and brake control units are used for brake control. The brake rectifier is used in the case of AC connection and the brake control unit in the case of 24 V_{DC} connection. For reasons of space, both are installed in the switch cabinet and not in the terminal box.

The brake rectifier is designed as a one-way rectifier with protective circuits against overvoltages, and integral control electronics to shorten the response times of the brake.

Brake response times

Brake motor frame size	56B	**71B**				**90B**				**112B**			
Braking torque [Nm]	2.5	3	6	10	15	12	20	30	40	17.5	35	60	90
Brake release Brake release reaction time t_1 [ms]	7	10	12	16	20	13	15	18	22	11	14	22	35
Brake application Brake reaction time t_2 [ms]	5	95	45	20	8	28	20	13	10	130	60	32	20

For 24 V_{DC} supply the BSG brake control unit is available. It corresponds in function to the BME brake rectifier with the difference that because brake control is with direct current, the brake control unit does not have a brake rectifier.

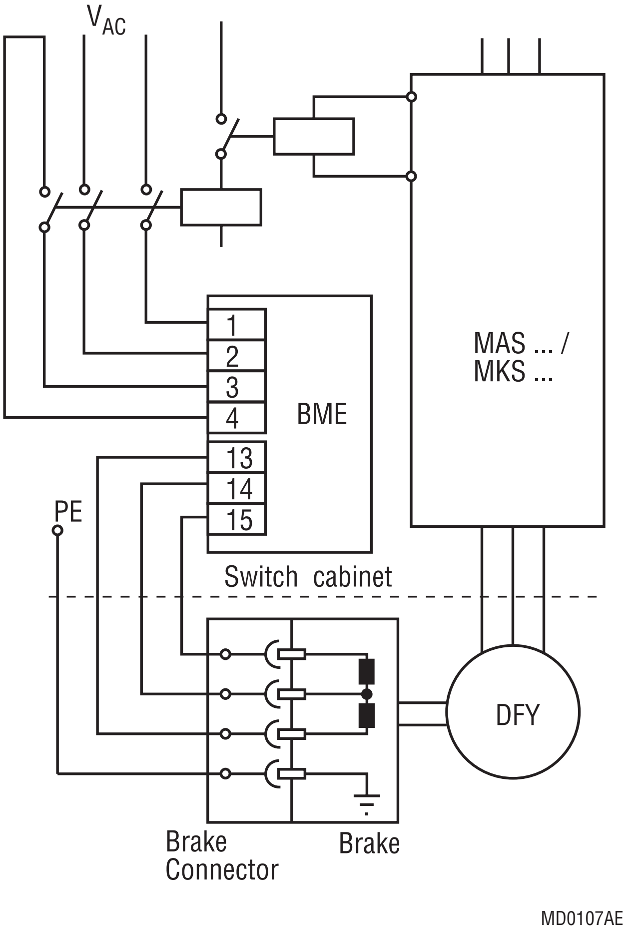

Fig. 20: Brake control

Figure 20 shows a brake rectifier for the switch cabinet. The brake rectifier is wired to disconnect both the DC and the AC circuits, i.e. fast application of the brake. Rapid excitation is also obtained with this type.

You will find more detailed information about the brake in “Drive Engineering - Practical Implementation”, Volume 4.

3 The resolver

3.1 Design and function of the resolver

The resolver operates on the principle of a rotary transformer. In a rotary transformer the rotor consists of a coil (winding) which together with the stator winding forms a transformer.

The resolver is basically designed exactly this way, with the difference that the stator is made up of two windings displaced by 90° to one another, instead of one winding.

The resolver is used to determine the absolute position of the motor shaft over one revolution. Furthermore, the speed and the encoder simulation for the position control are derived from the resolver signal.


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Fig. 21: Resolver

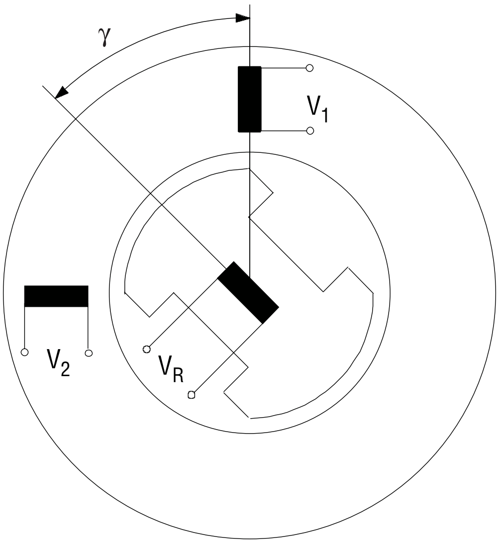

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Fig. 22: Schematic design

The rotor of the resolver is mounted on the motor shaft. Both the stator and the rotor are provided with an additional winding each to allow for brushless transmission of the stator primary voltage to the rotor. With the aid of these additional windings the primary voltage of the stator winding is transmitted on the transformer principle. The two windings carried on the rotor are coupled electrically so that the voltage transmitted from the stator to the rotor is also present on the second winding of the rotor.

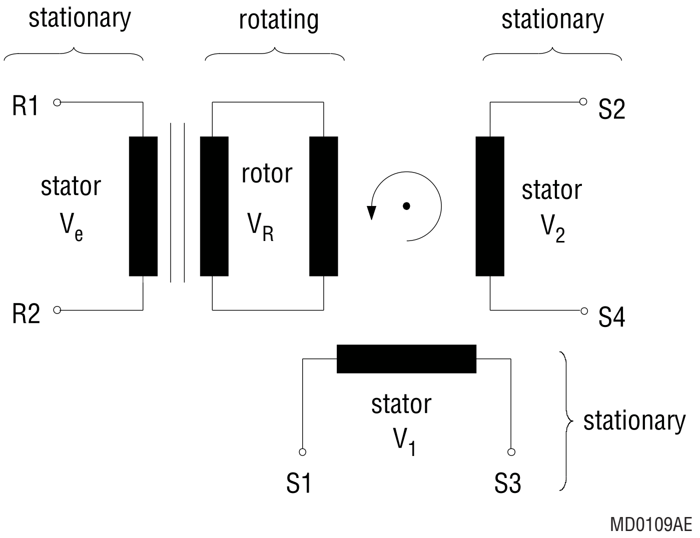

Fig.23: Resolver block diagram

Voltages of different magnitude are induced in the stator windings, depending on the position of the rotor. The winding through which there is full current flow at $\gamma = 0°$ (see Fig. 22) has the maximum voltage present at this point in time. If the rotor is rotated, then voltage V_1 on this winding decreases until it has attained the value zero at an angle of 90°. If the rotor is further rotated, the voltage again increases with inverse polarity until it has again reached its maximum at 180°. Voltage V_1 has a cosine curve as envelope. Voltage V_2, which is displaced by 90° to voltage V_1, has a value of 0 V at 0°. It increases until it has attained its maximum value at 90°, and then decreases again. The envelope of V_2 is therefore a sine curve.

The output voltages U_1 and U_2 are calculated as a function of the input voltage V_e as:

Input: $V_e = V_S \cdot \sin\omega t$ (reference voltage)

Output: $V_1 = V_S \cdot \sin\omega t \cdot \cos\gamma$

$V_2 = V_S \cdot \sin\omega t \cdot \sin\gamma$

where γ = rotor angle

ω = angular frequency of V_e

V_S = input voltage peak value

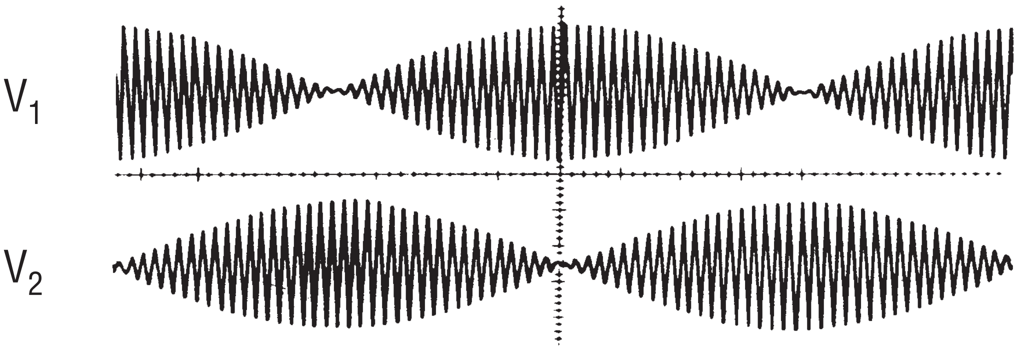

Fig.24: Output voltages V_1 and V_2 of the resolver

3.2 Processing and evaluating the resolver signals

The signals of the resolver are converted in the R/D converter (resolver/digital converter) into a digital numerical value. This digital value can be further processed to obtain additional information. The R/D converter provides information on the rotor position. Using the count value, the speed of the motor can be determined by counting the number of pulses within a specific time window, which then serves to determine the speed. The two least significant bits of the of the count value can be evaluated:
- for encoder simulation to determine the speed
- for higher-level positioning controls.

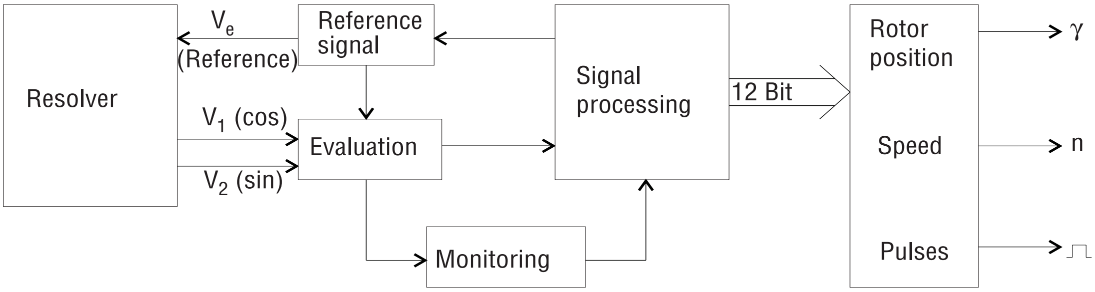

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Fig. 25: Processing of resolver signals

The oscillator [1] (see Fig. 26) feeds the rotor via the stator winding with an AC voltage of about 10 V_{rms} and a frequency of about 7 kHz. The digital numerical value of the up-down counter [6] is then converted in a D/A converter [5]. The output signals V_1 and V_2 of the stator of the resolver are multiplied by the sine or cosine of the converted value. The value of the up-down counter represents the angle φ. As a result, the two voltages below are produced:

$$V_{F1} = V_S \cdot \sin\omega t \cdot \sin\gamma \cdot \cos\varphi$$

$$V_{F2} = V_S \cdot \sin\omega t \cdot \cos\gamma \cdot \sin\varphi$$

The two multiplied output signals are subtracted from one another in the error amplifier [2]. The difference corresponds to the error (deviation) between the angle φ and the actual angle γ. The error is:

$$V_{FD} = V_S \cdot \sin\omega t \cdot (\sin\gamma \cdot \cos\varphi - \cos\gamma \cdot \sin\varphi)$$

Simplified, this equation is:

$$V_{FD} = V_S \cdot \sin\omega t \cdot \sin(\gamma - \varphi)$$

This signal is demodulated in the phase-selective rectifier [3] - which is downstream of the subtractor [2] - in order to remove the carrier frequency. The signal arising at the output of the rectifier is the error voltage V_F, which is proportional to sin (γ - φ).

This voltage is applied simultaneously to an output of the R/D converter and the input of the integrator [4]. The integrator [4] integrates the error voltage which is applied to the input of a voltage-controlled oscillator (VCO) [7].

If there is an angular difference between the angles γ and φ, the integrator produces a DC voltage from it. Using this DC voltage, the VCO [7] produces pulses, which are then processed in the up-down counter [6].

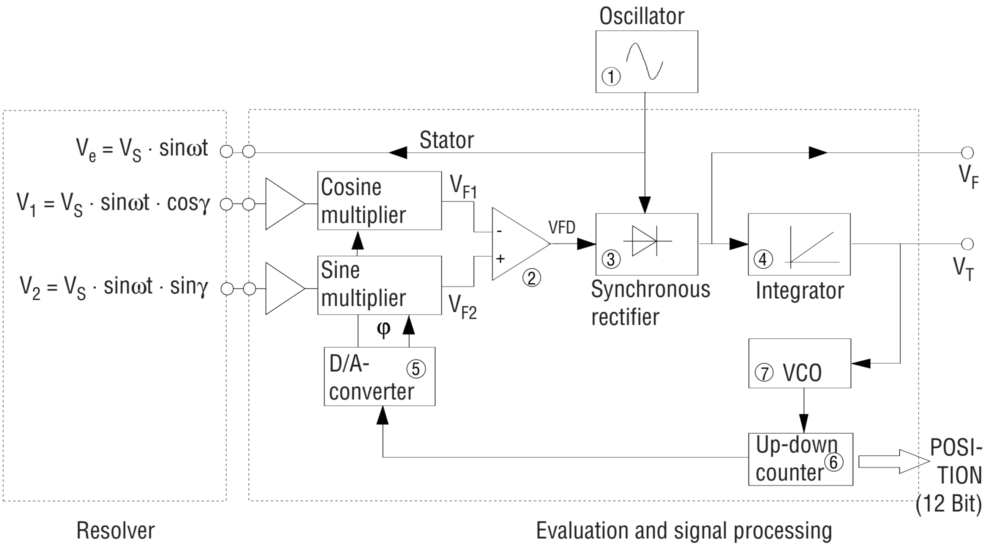

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Fig. 26: Block circuit diagram of an R/D converter

The modules [2] to [7] form a closed-loop control circuit. A DC voltage signal is present at the VCO [7] until the difference between the angles γ and φ equals zero, i.e. until:

$$\gamma = \varphi$$

Thus the digital value of the up-down counter corresponds to the analogue value of the angle γ of the resolver present at the input of the R/D converter.

Over a continuous turn of the resolver the VCO must produce pulses until the count value of the V/R counter corresponds to the analogue value of the rotor angle at the input, i.e. the angular variation of the resolver is offset. Consequently, the frequency of the VCO is proportional to the speed of the motor and the resolver. From this it follows that the output voltage of the integrator is also proportional to the speed.

The R/D converter supplies a direct voltage V_T at the outputs, which is proportional to the speed, plus absolute information for one revolution of the resolver.

The evaluation circuit is implemented as an integrated circuit, only the oscillator [1] is connected externally.

The error of the resolver signal is negligible (< 0.05%).

3.3 Encoder simulation

The encoder simulation produces a total of six tracks from the already available output signals of the resolver. These are used by higher-level controls for positioning. The six tracks are A, B and C and their negations $\overline{A}$, $\overline{B}$ and $\overline{C}$.

The encoder simulation provides 1024 pulses per revolution. Through quadruple evaluation 4096 pulses per revolution are available for positioning controls.

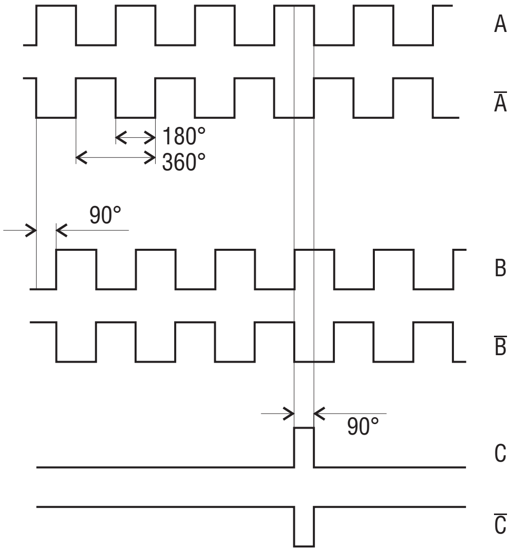

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Fig. 27: Encoder simulation

The pulses of tracks A and B are displaced by 90°. If the positive edges of the pulses of track A lead those of track B, then the motor is rotating clockwise. If track B leads track A by 90°, the motor is running counterclockwise.

For each full revolution of the motor, i.e. when going through zero position, track C supplies a pulse:

The motor's direction of rotation can be determined with the aid of the two least significant bits (LSB) of the signal processing.

2^1	2^0
0	0
0	1
1	0
1	1

↓ Clockwise

↑ Counterclockwise

Function table of the two LSBs

For clockwise (positive) rotation the counter in the R/D converter counts up. The function table is then read from top to bottom. Each time the least significant bit 2^0 changes from 1 to 0, the value of bit 2^1 changes too.

If the motor's direction of rotation changes, the function table must be read from bottom to top correspondingly. In this case, however, when the least significant bit 2^0 changes from 1 to 0, the value of bit 2^1 does not change.

4 The servo controller

The servo controller is used for speed and torque control of the servo motor. Nowadays, this is normally a digital controller. The digital controller has the following advantages over the analogue controller:

- more resistant to ageing
- drift-free
- simple communication
- computer operations easily implemented

Servo controllers are used both in the form of compact servo controllers (so called stand-alone units) as well as in modular designs.

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Fig. 28: Servo controllers in modular design

MD0104AX

Fig. 29: Compact servo controller

Stand-alone units have the advantage that the servo controller is available as a complete unit. At the same time, the additional wiring between the individual unit components - as is necessary in the modular system - is eliminated.

The advantages of the modular digital servo controller (power supply module + axis module) are in multi-axis applications. Several axis modules can be supplied by one common power supply module in multi-axis applications. The required output capacity of the power supply module is determined from the total power requirements of the connected axis modules and their utilization.

A digital servo controller of modular design is described in the following sections.

4.1 Basic components of the modular system

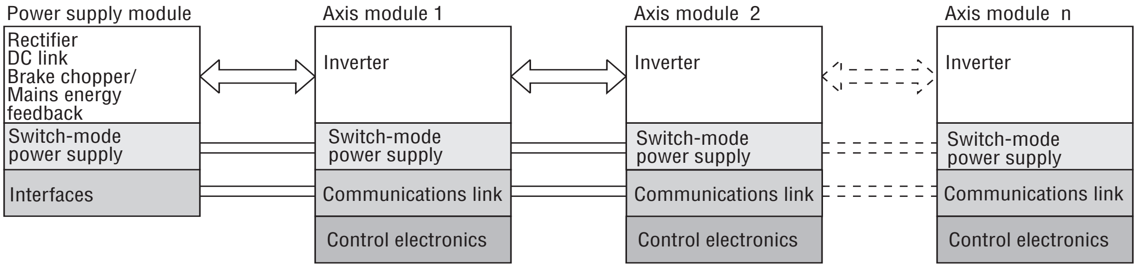

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Fig. 30: Structure diagram of a modular servo controller

The modular servo controller consists of two basic components

- power supply module
- axis module

The power supply module is used for the power supply to the connected axis modules via the DC link, and for the voltage supply to the control electronics. It also contains the central brake chopper or the mains energy feedback unit, various protective features and standardized communications interfaces (RS-232 and RS-485).

The axis module controls speed and torque of the servo motor. It contains the control electronics needed for this, permanently assigned and freely programmable binary inputs and binary outputs, analogue inputs, analogue outputs, the output for the encoder simulation and a free slot for the option pcbs.

The number of axes which can be connected to a power supply module is limited by the:

- output capacity of the power supply module
- output of the switch-mode power supply
- maximum braking power
- line length of the DC link, the data line bus connection (interference immunity) and the 24V bus connections.

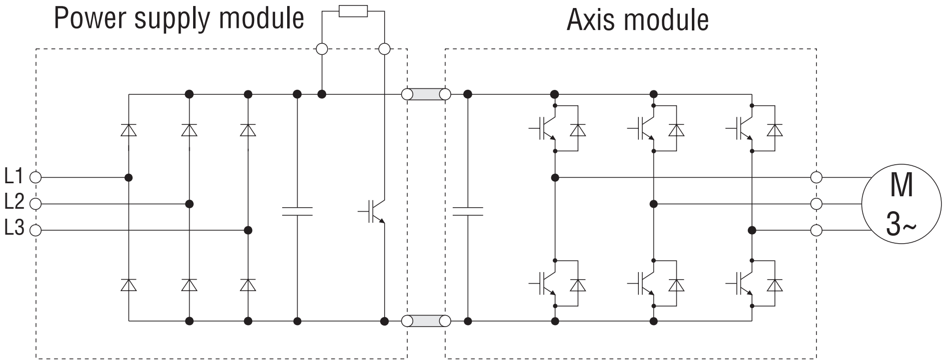

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Fig. 31: Power section of a servo controller

The power section of the servo controller is based on the principle of the static voltage DC link converter. This means that capacitors keep the voltage stable on the DC link. The output stage or power inverter transistors are IGBT transistors. Their advantages are low switching losses, simple control, low forward power losses and high switching frequencies.

4.2 Power supply module

The power supply module is connected to the three-phase mains supply through a line choke on the supply side. The supply voltage range is 3 · 380 ... 500 V. The line choke, in conjunction with design measures in the power section of the controller, completely replaces other customary inrush current-limiting charging components. It minimizes noise on the supply lines and is part of the unit protection features against transient overvoltages.

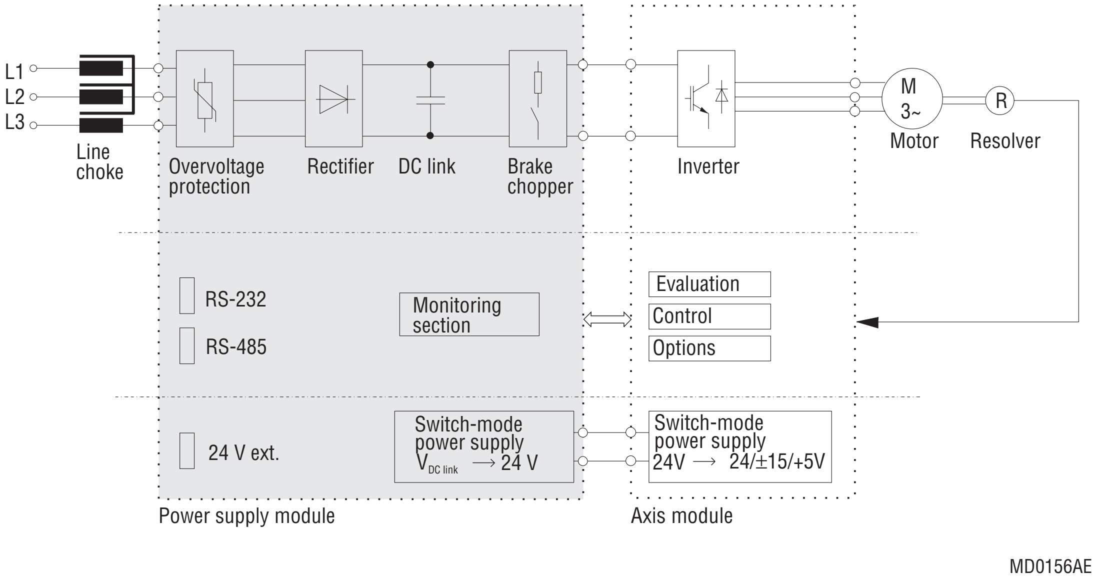

Fig. 32 : Block circuit diagram of a modular servo controller

The power supply module includes the following monitoring features:

- DC link overvoltage
- mains phase failure
- earth fault
- overtemperature
- brake chopper overcurrent protection

4.2.1 Rectifier and overvoltage protection

Inside the power supply module a surge suppressor circuit protects the power section against damage that may be caused by voltage peaks in the supply lines, which occur when inductive and capacitive loads are connected to the mains.

The overvoltage protection is implemented by means of capacitors, surge arresters and varistors.

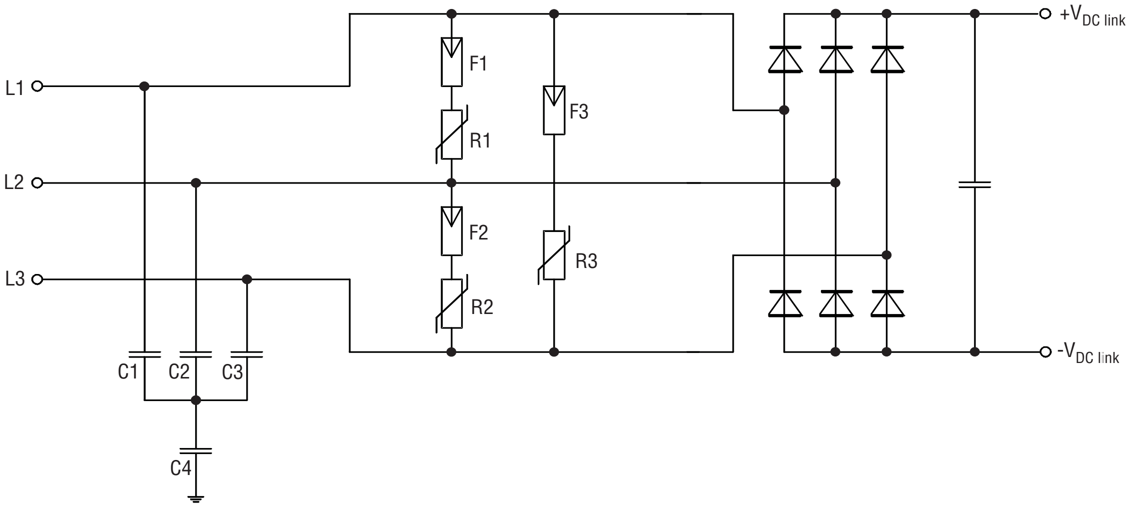

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Fig. 33: Rectifier and overvoltage protection

The input rectifier is a three-phase bridge rectifier.
This rectifier turns the AC voltage into a DC voltage,
the DC link voltage $V_{DC\ link} \approx \sqrt{2} \cdot V_{rms}$.

4.2.2 DC link and mains energy feedback

When a drive is decelerating kinetic energy is converted into electrical energy and this is fed back into the DC link. As the capacity of the DC link capacitor is limited, the voltage in the DC link rises. To enable the drive to decelerate, this additional energy must be dissipated.

It is therefore necessary to store the regenerated energy or to convert it into other forms of energy.

There are basically three possibilities for this:

- energy feedback to the mains (the electrical energy can be used by other consumers)
- brake chopper and braking resistor (the energy is converted into heat)
- exchange of energy in multi-axis applications (the electrical energy is used by other connected motors).

4.2.2.1 Supply energy feedback

The advantage of the mains energy feedback is that the energy is fed back into the supply network and therefore remains available as electrical energy.

There are various options for implementing mains energy feedback, one is the anti-parallel bridge. With this form of mains energy feedback, the mains rectifier is expanded by a bridge circuit of six power transistors which are triggered synchronously with the mains. If the DC link voltage exceeds the rectifier value, then regenerated energy is fed back into the supply.

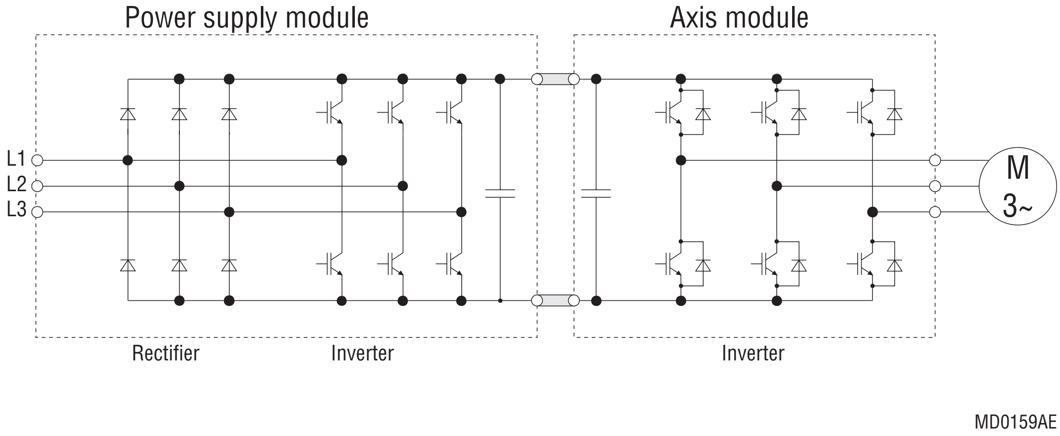

Fig. 34: Mains energy feedback

4.2.2.2 Brake chopper and braking resistor

In contrast to mains energy feedback, the produced energy is not fed back into the supply but converted into heat by the braking resistor. If only little braking energy is produced it may be less expensive to use a brake chopper rather than the mains energy feedback.

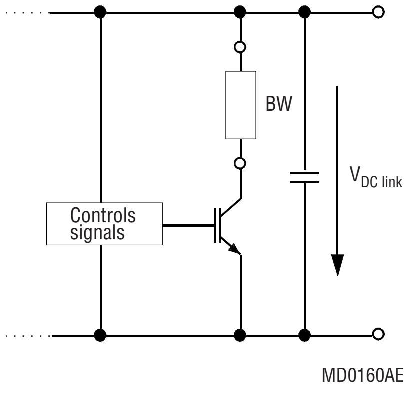

Fig. 35: Brake chopper

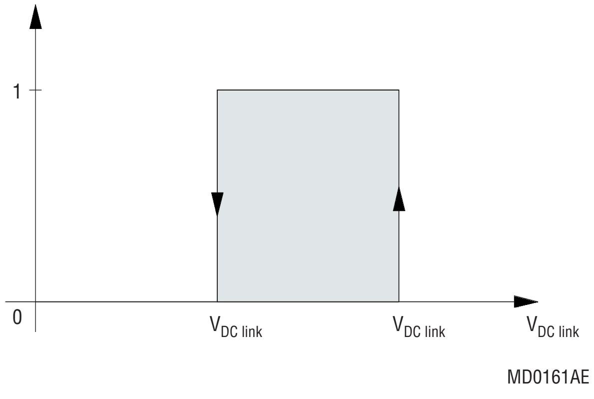

Fig. 36: Switching behaviour of the brake chopper

4.2.2.3 Comparison between mains energy feedback and brake chopper

A decision must be made as to which method is most suitable for a given application and its specifics.

	Mains energy feedback	**Brake chopper and braking resistor**
Location	Completely integrated in the power supply module	Brake chopper in the power supply module, braking resistor externally or in the switch cabinet
Effect on the ambient temperature	Minor	Heat generation on the brake resistor
Wiring	None	Connection to external brake resistor required
Energy balance	Conservation of electrical energy	Electrical energy is converted into heat
Cost factor	Control electronics, inverter	Control electronics, switching transistor, braking resistor, mounting, wiring
EMC requirements	Minor	Screened leads to braking resistor

4.2.3 Serial interfaces

The axis modules can be parameterized using a PC, through the integral standard RS-232 interface in the power supply module. The RS-232 interface is used for communication between two communication units, e.g. PC and axis module.

The RS-232 interface can be made “busable” in combination with the RS-485 interface, which is also integrated in the power supply module. This allows up to 31 physical or 59 logical axes, which are interconnected via the RS-485 interface of their power modules to set parameters through the RS-232. Each axis only needs its individual address.

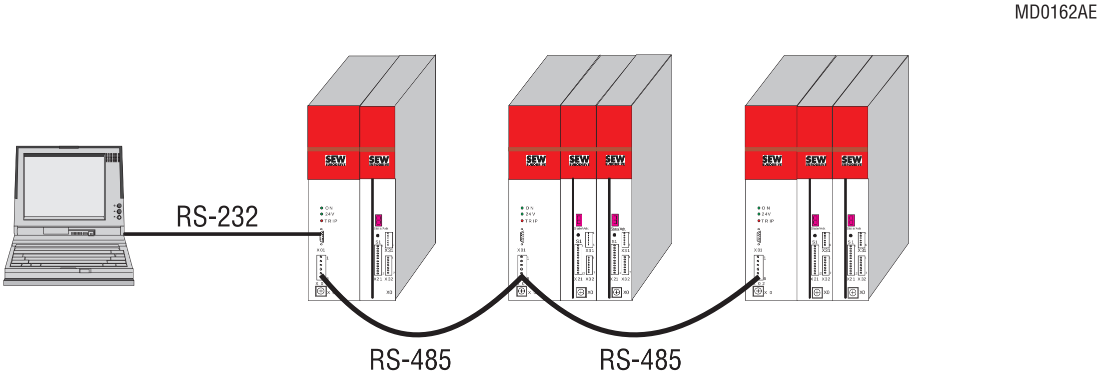

Fig. 37: Communication via serial interfaces

4.2.4 Electronics supply

The power supply module contains a central switch-mode power supply (SMPS) for supplying the electronics. This produces a DC voltage of 24 V from the DC link voltage $V_{DC\ link}$. This voltage is required for supplying the monitoring electronics. At the same time, all axis modules connected to the power supply module are fed with this voltage from the 24 V bus.

The power supply module also offers the option of connecting an external 24 V supply. The control electronics remain operative by this external voltage, i.e. rotor position information and error messages are retained, even if the main voltage supply is interrupted. This is important, in particular for operating a drive with positioning control, because no further reference travel is needed if the main voltage fails.

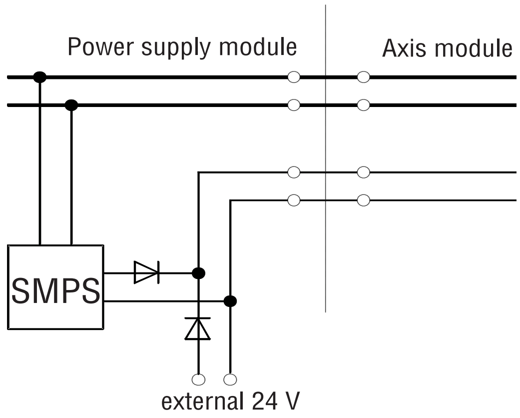

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Fig. 38: 24 V supply

Also, the external 24 V power supply enables the user to parameterize the axis modules if the DC link is not energized.

4.3 Axis module

The axis modules are connected to the DC link and the protective earth conductor by means of busbars. A separate 24V bus is used for the control electronics power supply. A data bus is installed on the unit underside to enable a PC or a higher-level control (PLC) to communicate with the connected axis modules (this bus is not directly accessible to the user).

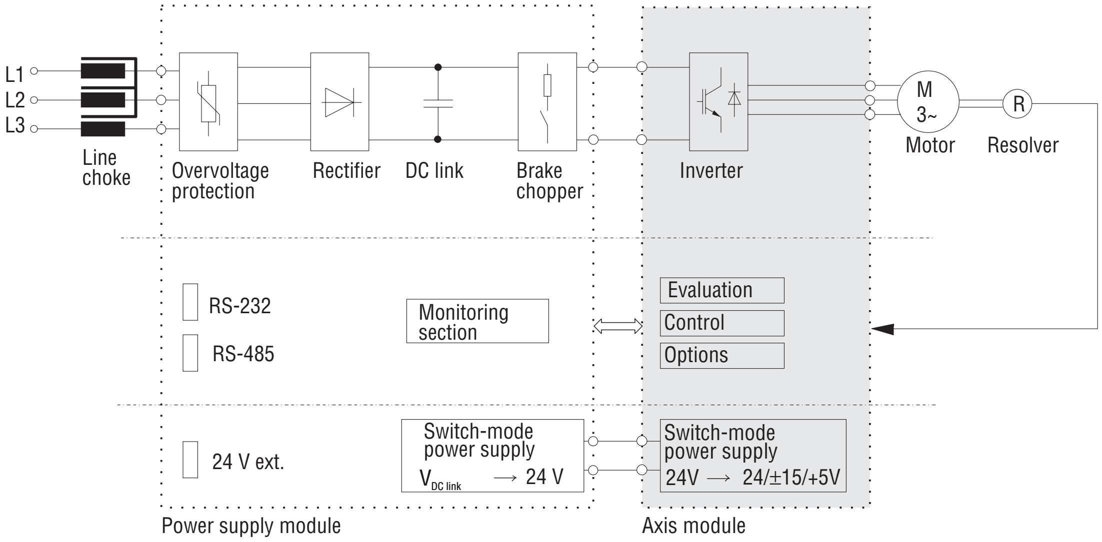

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Fig. 39: Block circuit diagram of a modular servo controller

The axis modules can be operated under speed control or torque control. They supply sinusoidal output currents, so that precise, true running with minimum torque ripple is ensured even at low output speeds. The sinusoidal output currents minimize additional motor losses and ensure good utilization of the motor power.

The axis modules and option pcbs parameters are set from a PC via the standard RS-232 interface or from a PLC via the RS-485 interface.

Optional bus interfaces are also available for parameter adjustment.

4.3.1 Design of the axis module

In the axis module, the functions of control, evaluation (resolver evaluation, current controller) and options (additional terminals, positioning control) are implemented in modular design. The advantage of this card-rack system is that other control procedures (e.g. V/f or flux vector control) can be used by simply exchanging the control pcb and/or the evaluation pcb.

Figure 41 shows the interrelationships in the axis module. The functions of the individual blocks are shown in the next sections and in the description of the control structure.

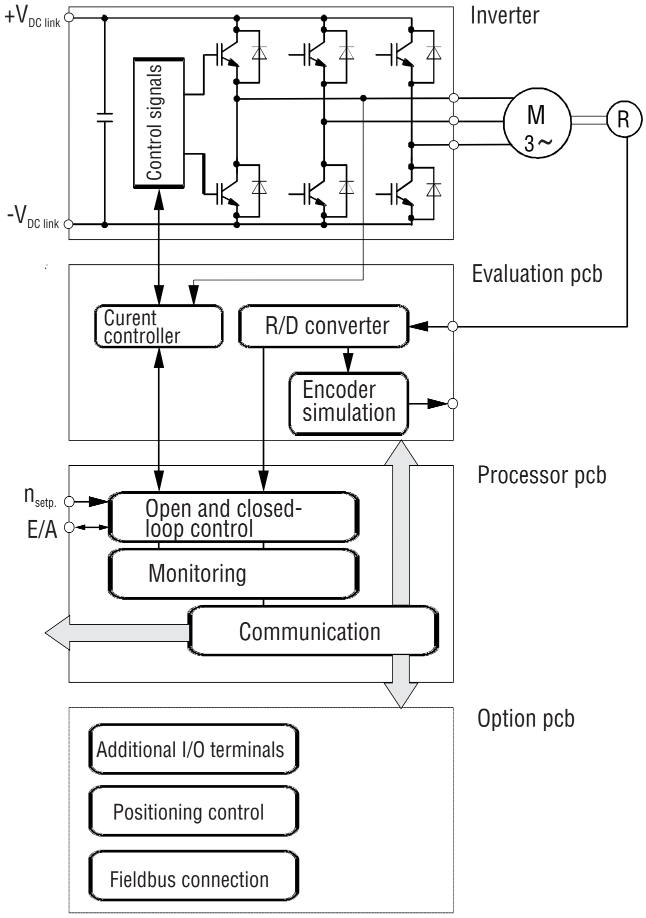

Fig. 40: Interrelationships in the axis module

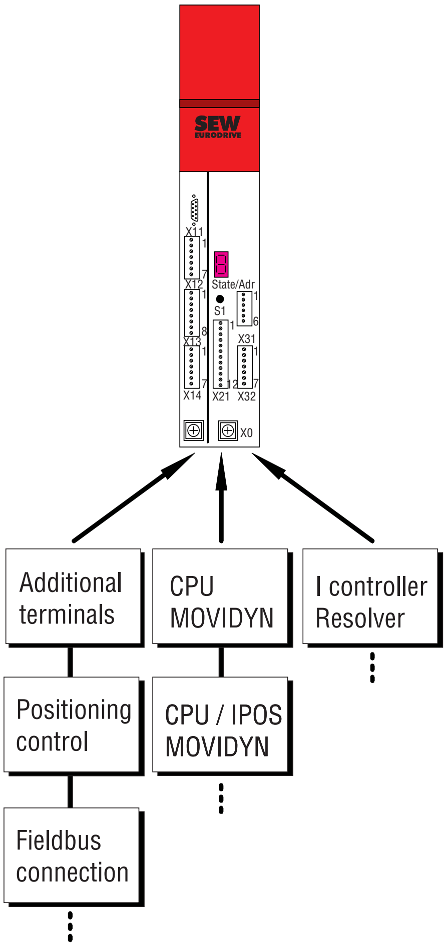

Fig. 41: Modular design

The power inverter

The power inverter is supplied via the DC link voltage $V_{DC\ link}$. The power transistors are switched by the associated triggering circuit so that a pulse-modulated voltage is present at the output of the axis module and thus, at the motor. The pulse width is determined by the current controller output. This pulse width-modulated voltage produces a current in the motor which is almost sinusoidal because of the motor and cable inductances.

A diode is connected in parallel to each power transistor. These free-wheeling diodes prevent self-induced voltages from damaging the power inverter. These occur with inductive output loads at the moment of switching. The diodes feed the stored energy back to the input of the power inverter. They also exchange reactive energy between the motor and the inverter.

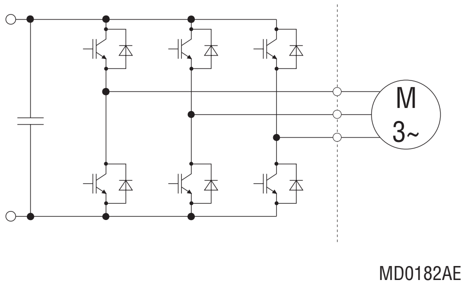

Fig. 42: Power inverter

Evaluation pcb functions

The evaluation pcb includes the following features:

- resolver evaluation
- encoder simulation
- current control

The resolver evaluation and the encoder simulation have already been described in the preceding sections.

The current controller is of analogue design. The current controller is set at the factory, and its setting matched to the connectable motors.

Control pcb functions

The control pcb carries the microprocessor and its peripherals. The main functions of the microprocessor are:

- speed control with great flexibility
- hold control
- an internal positioning control (option)
- extensive monitoring functions of system variables, inputs/outputs and control functions
- communication between microprocessor, evaluation and option pcbs through the backplane bus
- communication with other axis module(s)

4.3.2 Options

AIO11 terminal expansion

The AIO11 option expands the control and monitoring possibilities of the axis modules with additional digital and analogue inputs and outputs and a serial interface.

API/APA and IPOS positioning controls

Positioning controls are a simple means of implementing motional sequences, precise positioning and holding of a position (position control).

The advantages offered by these option pcbs which use different feedback systems are:

- reduced space requirement in the switch cabinet
- voltage supply by servo controller
- digital setpoint input for the speed
- programming through existing standard interfaces (RS-232, RS-485) of the axis module
- direct I/O control signal access

With IPOS integrated positioning the option slot remains free. This allows for the use of additional options (i. e. PROFIBUS, INTERBUS-S, CAN-BUS).

Fieldbus interfaces

Interface pcbs are available for standardized fieldbus systems widely used in automation environments (e.g. PROFIBUS, INTERBUS-S, CAN-BUS).

The fieldbus pcbs plug into the free option pcb slot. Through the fieldbus control signals, process data and parameter values can be transmitted between the higher-level control system and the servo controller.

5 Control structure / Modes of operation

Electrical servo drives are used for position control in many types of application. To achieve a good control response, the position controller itself has an inner speed controller and a current controller.

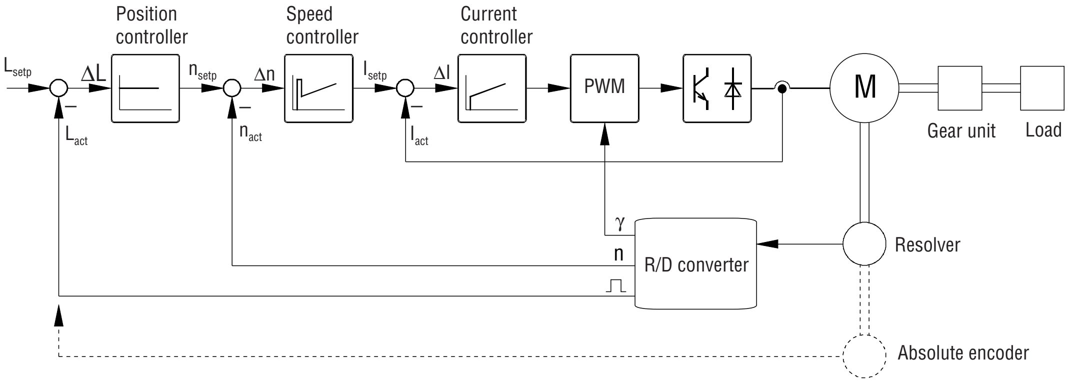

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Fig. 43: Servo system control structure

The external position setpoint is the reference variable used by the servo controller. The error between position setpoint and position actual value is the input for the position controller, which outputs the relevant setpoint speed n_{setp} for the motor.

The speed setpoint and actual values are compared in the lower-level speed controller. The error is subject to PI control in the speed controller.

The output signal from the speed controller is the current setpoint and is routed to a limiter circuit to protect the motor and inverter. The output signal from the limiter circuit itself becomes the setpoint value for the current controller. The current actual values are converted into a DC signal by a rectifier circuit. The current controller compares the setpoints and actual values and uses a pulse width modulator (PWM)to generate the control signals that are routed to the control stages of the individual power transistors of the inverter.

With the exception of current control, all open and closed-loop control and monitoring functions are handled by a microcontroller. Current control is designed as an analogue circuit to satisfy speed requirements.

5.1 Current controller

The current controller is designed as a PI controller. The input variable is the difference between the current setpoint and actual values for a motor phase; the output is the control voltage for the pulse width modulator. This uses a sinusoidal-delta comparison to generate a pulse-width modulated voltage for controlling the inverter.

The current actual value is measured on the inverter output using a DC instrument transformer and passed to the comparator on the input of the current controller.

The current controller is the innermost control loop of the servo controller and must therefore respond very quickly, as this will determine the speed of all the higher-level controllers.

A current limiter is situated upstream of the current controller. This limiter limits the setpoint current to a predetermined maximum value.

The maximum current is determined by the three possible factors listed below:

- thermal model (protects the output stage at low frequencies)
- limiting by internal parameters
- limiting by external inputs

The following block diagram shows the current controller and the three factors that determine the current limit:

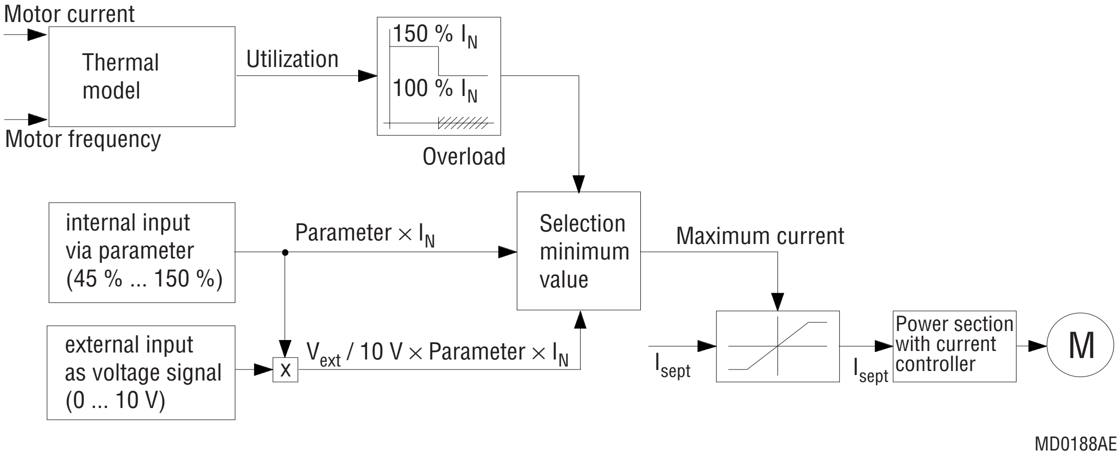

Fig. 44: Current controller with current limiting

Limiting of the setpoint current using the thermal model is only effective at frequencies of up to 1.5 Hz. Within this frequency range, the current has to be limited as the conduction interval within the output stage will otherwise be too long, with the result that the output stage will become too warm.

Under normal operating conditions, the output stage can handle up to 150 % of the continuous rated current. At frequencies lower than 1.5 Hz, this threshold sinks to about 100 % I_N. If the motor is being driven at less than 1.5 Hz, a current greater than 100 % I_N is only permitted for a short time. If this permitted period is exceeded, the maximum current value is reduced to 100 %.

One of the reasons for limiting the current through an internal parameter is to protect the motor. The parameter is entered in the controller menu, depending on the maximum motor current. It can have a maximum value in the range 45 to 150 % I_N.

Limiting the current through an external input is only possible with the AI011 option pcb.

The input signal is a voltage from 0 to 10 V. This voltage is set in proportion to the maximum voltage in this range. The quotient of the two voltage values is multiplied by the set maximum current value. The maximum current defined externally can therefore only be less than or, at the most, equal to the one defined internally.

It is always the limit with the lowest value that is effective.

Example: The maximum motor current ($3 \cdot I_0$) is 110 % of the rated current of the servo controller. The motor is being operated at a frequency greater than 1.5 Hz.

The requirements for external input of the maximum current are given and a voltage of 8 V is present on the analogue input for external current input.

- Limiting using the thermal model has no effect as the frequency of the motor is not within the effective range for the model (< 1.5 Hz).
- The internal parameter is programmed to 100 % of the rated current as this corresponds to the maximum permitted motor current.
- The external value for the maximum current is entered as 8 V. In proportion to the maximum possible voltage on this input of 10 V, this gives a factor of 0.8 (= 80 %). The internally defined maximum current is multiplied by this factor.

  $0.8 \cdot 110\,\% \cdot I_N = 88\,\%\ I_N$

The smallest maximum current value specified is therefore the current value of 88 % I_N on the analogue input.

5.2 Speed controller

To ensure that the speed control has the required wide control range, even very low speeds still need to be detected accurately, a high-resolution rotor-position encoder and an extremely short sampling time are required. This in turn demands a high processing speed and hence a particularly powerful processor.

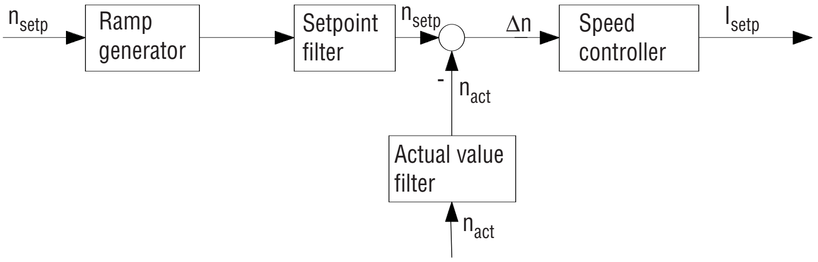

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Fig. 45: Speed controller

The speed controller is superimposed on the current controller. It obtains the setpoint speed through:

- positioning control
- analogue input
- fieldbus interface
- serial interface

The speed controller is designed as a PID controller. All three controller components can be set separately. In most applications the D component is set to zero because of its difficult adjustment and optimization in order to prevent possible overshoot of the drive.

5.2.1 Speed filter

Speed setpoint filter

Speed setpoint filters are necessary because:

- analogue speed setpoints often contain errors
- the speed setpoint value of the higher-level positioning control is “staircased” because of the control’s cycle time.

The diagrams below show the curve of the speed setpoint and the torque at the motor without filter and in comparison with the ideal curve of the two variables.

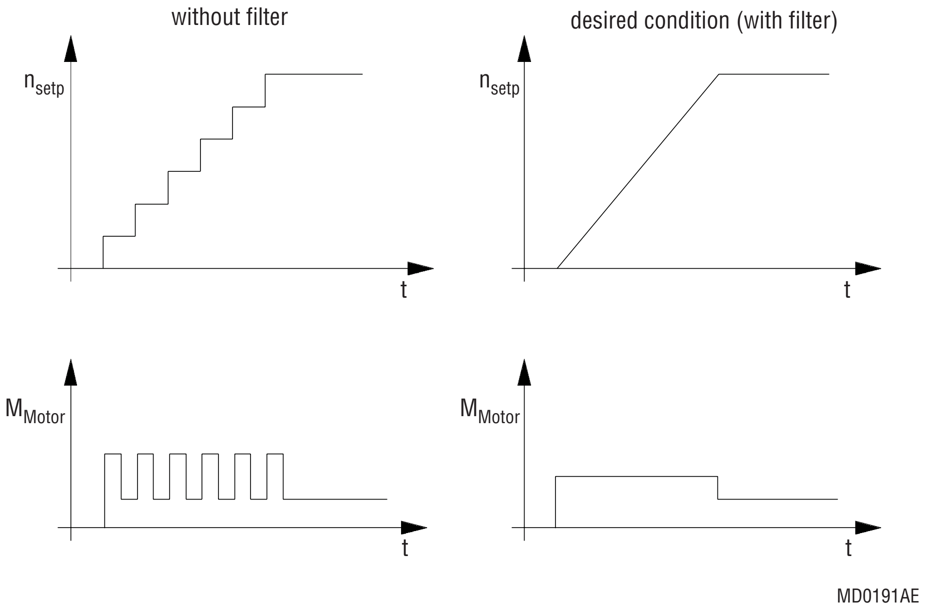

Fig. 46: Speed setpoint filter

The diagram of the setpoint speed without filter shows a staircased signal of a positioning control which causes a pulse-type curve of the motor torque. In contrast, a continuous curve of the setpoint speed (and thus also of the motor torque) can be seen with the use of a speed setpoint filter.

Speed actual-value filter

Speed actual-value filters are needed to filter out noise. This causes difficulties, particularly in the range of lower speeds.

The time constant of a filter must be chosen so that the dynamic response of the drive is not restricted. If the time constant of the filter is too high, the system is slowed down and loses some of its dynamics.

5.2.2 Speed controller with feedforward

The aim of using a feedforward is a better controlled acceleration (improving the control response). The additional P component of the feedforward makes for faster completion of the acceleration process. Since the feedforward is only effective within a certain range, this has no effect on the system's control response in normal operation nor on its response to disturbances.

Speed control with feedforward is used if acceleration is to be completed fast. The feedforward is connected in parallel with the speed controller.

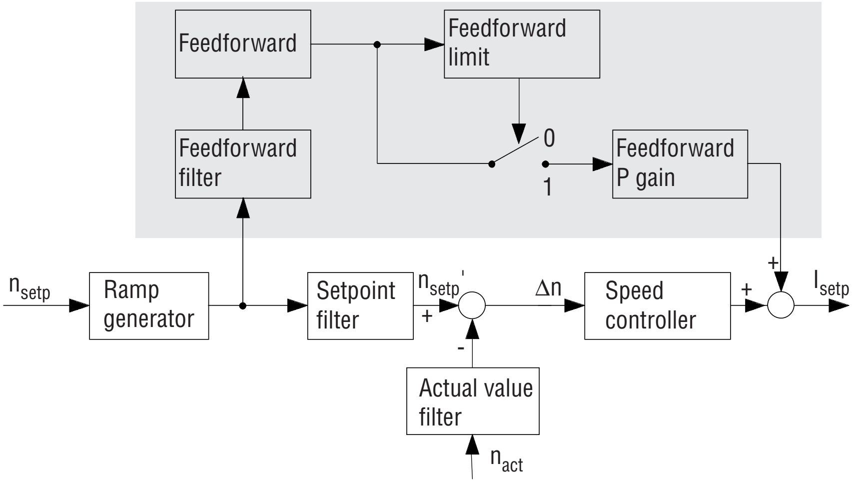

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Fig. 47: Speed controller with feedforward

The speed setpoint supplied by the ramp generator is filtered in the feedforward filter. The filtered signal is routed to a differentiator circuit. The magnitude of the differentiator output depends on the change of speed over time. If the value exceeds the trigger threshold of the feedforward, it is fed to a P element. The gain of the feedforward can be set at this P element. The output of the P element is in turn routed to the input of the current limiter circuit.

If the value falls below the trigger level again, the feedforward is inhibited and the speed controller is effective on its own again.

If a drive is operated without feedforward, a considerably higher I component is developed in the speed controller, which results in drive overshoot.

5.3 Position controller

The position controller is implemented as pure proportional controller. An integral component would result in impermissible drive overshoot when the target position is approached. The integral component of the lower-level speed controller makes sure that there is no constant position error (e.g. under load).

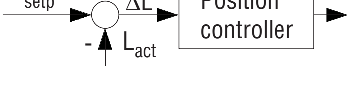

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Fig. 48: Position controller

Hold control

The hold controller is a variation of the position controller. It ensures that the original position is retained without the need for an external positioning control even if disturbances occur (e.g. loading or unloading of a hoist). The hold control is a special function which can be activated via a binary input. If the input goes high (logical "1"), the setpoint value "n = 0" (zero speed) is given to the speed controller. The drive ramps down the active setpoint ramps to zero speed. When zero speed is first detected by the speed detection system, the position actual value is stored as position setpoint value. At the same time, the output of the position controller is routed to the input of the speed controller. The system is now position-controlled at the position which has been stored as the setpoint value.

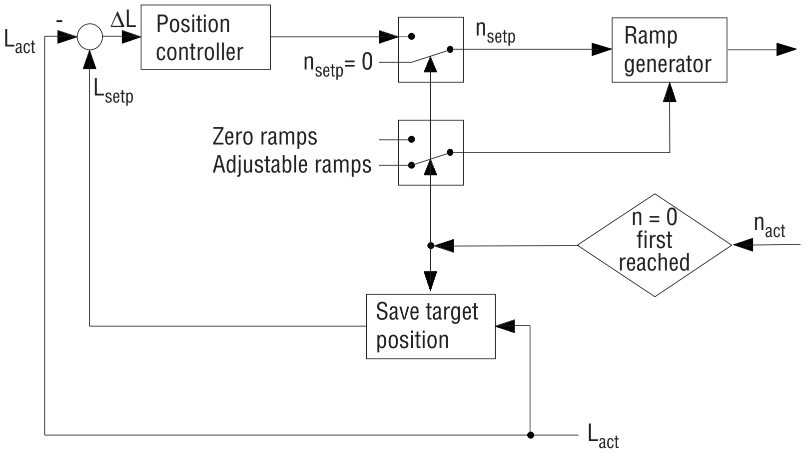

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Fig. 49: Hold control

5.4 Operating modes

Servo controllers are used in two different operating modes:

- speed control
- torque control

5.4.1 Speed control

Speed control consists of a speed control loop with upstream speed limiting. Speed limiting limits the setpoint value coming from the setpoint source to a maximum speed. If the drive reaches the setpoint speed or the maximum speed, it will stay at this speed and thus operate under speed control.

If the load on the motor is too great, the drive will reach the current limit before the motor attains the specified speed. If the load increases still further, the motor may come to a standstill. An error will only be detected if the "speed monitoring" function is active or when the temperature monitoring of the heat sink trips.

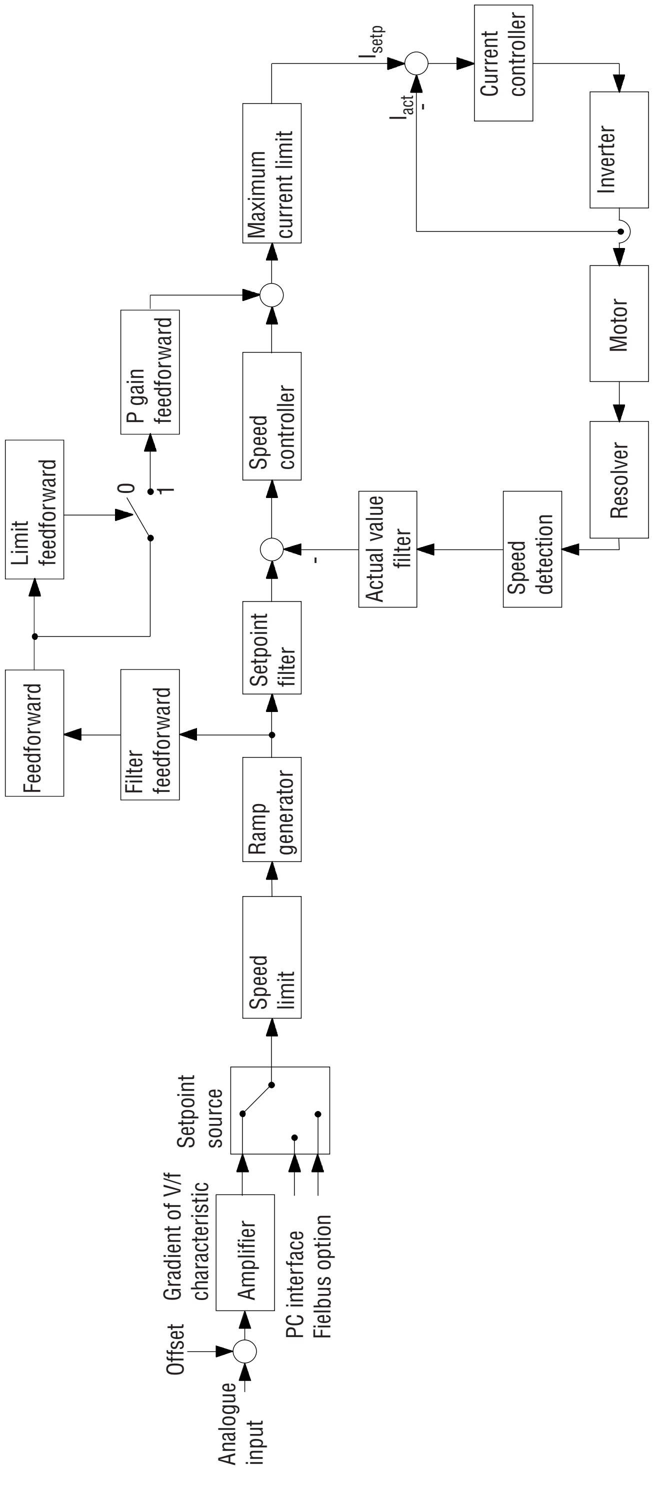

Fig. 50: Speed control

5.4.2 Torque control

Pure torque control of servo drives is mainly used in what is known as “current slaving” in master-slave applications.

The present current actual value of the master is passed to the slave as an input signal (setpoint). Both drives must be mechanically connected to each other (e.g. by a shaft). The slave will then deliver the same torque as the master and the load will be shared between the two drives.

Another application of torque control can be found, for instance, in winder drives.

In torque control, the speed controller is overridden. This means that the controller is always fully under control. The current limit is given by the setpoint torque, i.e. the current setpoint. The direction of rotation (n_{max} CW or n_{max} CCW input) is determined by the sign of the torque setpoint value.

When operating under torque-controlled conditions, the motor will not normally reach the specified speed value n_{max} as the current limit is active. The current value will then correspond to the setpoint current, i.e. the setpoint torque is reached. The motor is thus torque-controlled.

If the load torque is not sufficient to reach the setpoint current value, the motor accelerates up to the maximum speed n_{max}.

6 The gear unit

In its function as a converter of torque and speed, the gear unit is the central component of the geared motor.

6.1 Demands of gear units in servo technology

- low inherent mass moment of inertia
- low circumferential backlash
- high torsional rigidity
- high efficiency
- precision-balanced

A low-inertia gear unit is essential for high-dynamic drives. Whenever fast acceleration of a drive is a major requirement, use of a dynamic gear unit with as high an efficiency as possible is almost inevitable.

Extremely low circumferential backlash and high torsional rigidity are required when using a positioning control because otherwise relatively high angle errors occur which make accurate positioning impossible.

6.2 General overview of gear units

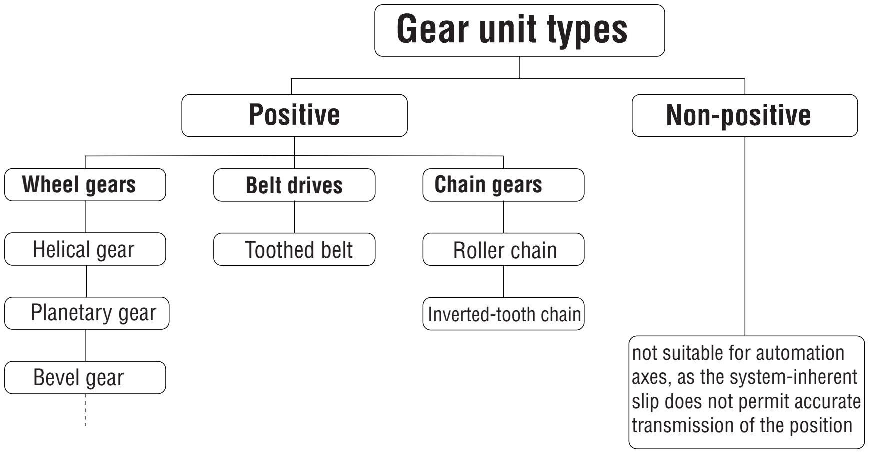

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Fig. 51: Overview of gear units

A distinction is made, according to the direction of the power flow, between coaxial or parallel shaft gear units and right-angle gear units. With coaxial and parallel-shaft gear units, the input and output shafts are in the same plane, and the power flow is linear. With right-angle gear units, the input and output shafts are at 90° to one another and the power flow is turned through a right angle.

In the following, the most common gear units used in servo technology are described.

6.2.1 Helical gear units

Helical gear units are the most commonly used gear unit. They are inexpensive to produce, require no complicated machine tools for manufacture and allow the use of controlled production methods. Their simple and rugged design suits most applications.

In helical gear units the input and output shafts run parallel to each other. This makes the overall drive short and slim, i.e. ideally suited for applications where space is tight. In this parallel shaft arrangement the output shaft is usually designed as hollow shaft, an advantage in particular in travel drives where the straight-through axle can transmit the force synchronously onto both drive wheels.

6.2.2 Planetary gear units

Low-backlash and torsionally rigid planetary gear units are most often used in dynamic applications.

Compared with helical gear units, the distribution of load onto several planetary gears results in a considerably higher power density and hence a lower unit volume. Planetary gear units ensure very low circumferential backlash (3 to 10 angular minutes) due to their optimized gearing geometry and highly exacting manufacturing tolerances. Generously dimensioned shaft diameters guarantee very high torsional rigidity and hence good positioning accuracy. Planetary gear units are also low-loss with efficiencies of η = 97% (single-stage gear unit) and η = 94% (two-stage gear unit) at 80°C operating temperature. They are also quiet and low-maintenance.

6.2.3 Helical-bevel gear units

Particularly compact drive solutions can be implemented with helical-bevel gear units where the power flow is turned through a right angle.

In helical-bevel gear units output shafts can be implemented as hollow shaft or as solid shafts.

6.3 Comparison of different gear unit types for servo technology

	Helical gear units	Planetary gear units	Helical-bevel gear units
Power density	medium	high	medium
Gear ratio per characteristic stage	small approx. i = 1 ... 8	medium approx. i = 4 ... 10	small approx. i = 1 ... 6
Circumferential backlash	medium	small to very small	medium
Torsional angle (at output)	α = 12’...18’	α = 3’...10’	α = 12’...18’
Torsional rigidity	medium	high	medium
Noise	medium	low	medium

7 Use in an industrial environment

7.1 Mains conditions

In the case of industrial mains, a sine-wave voltage is assumed. Unstable conditions normally have no effect. The controllers can be used with most types of mains (TN, TT, etc.).

Voltage fluctuations can affect how the drive works. Within the rated voltage range, the drive will function normally. If the range is exceeded, the drive will have to shut down to prevent damage occurring. If the voltage is too low, the motor will no longer deliver the rated values specified in the technical data. The mains voltage frequency is of minor significance.

The use of line chokes and protective circuits make the servo controllers immune to voltage spikes that can, for example, occur in reactive power compensation equipment systems without line chokes.

7.2 Notes on the motor

How to select a motor is shown in the project planning example. The motor and servo controller must be matched to each other.

Servo motors are usually fan-cooled. As heat dissipation is through convection, the colour and cleanliness of the motor are important.

The motors are protected to IP65 as standard. The continuous torque can be increased by a factor of 1.6 through the use of a forced cooling fan.

7.3 Cabling

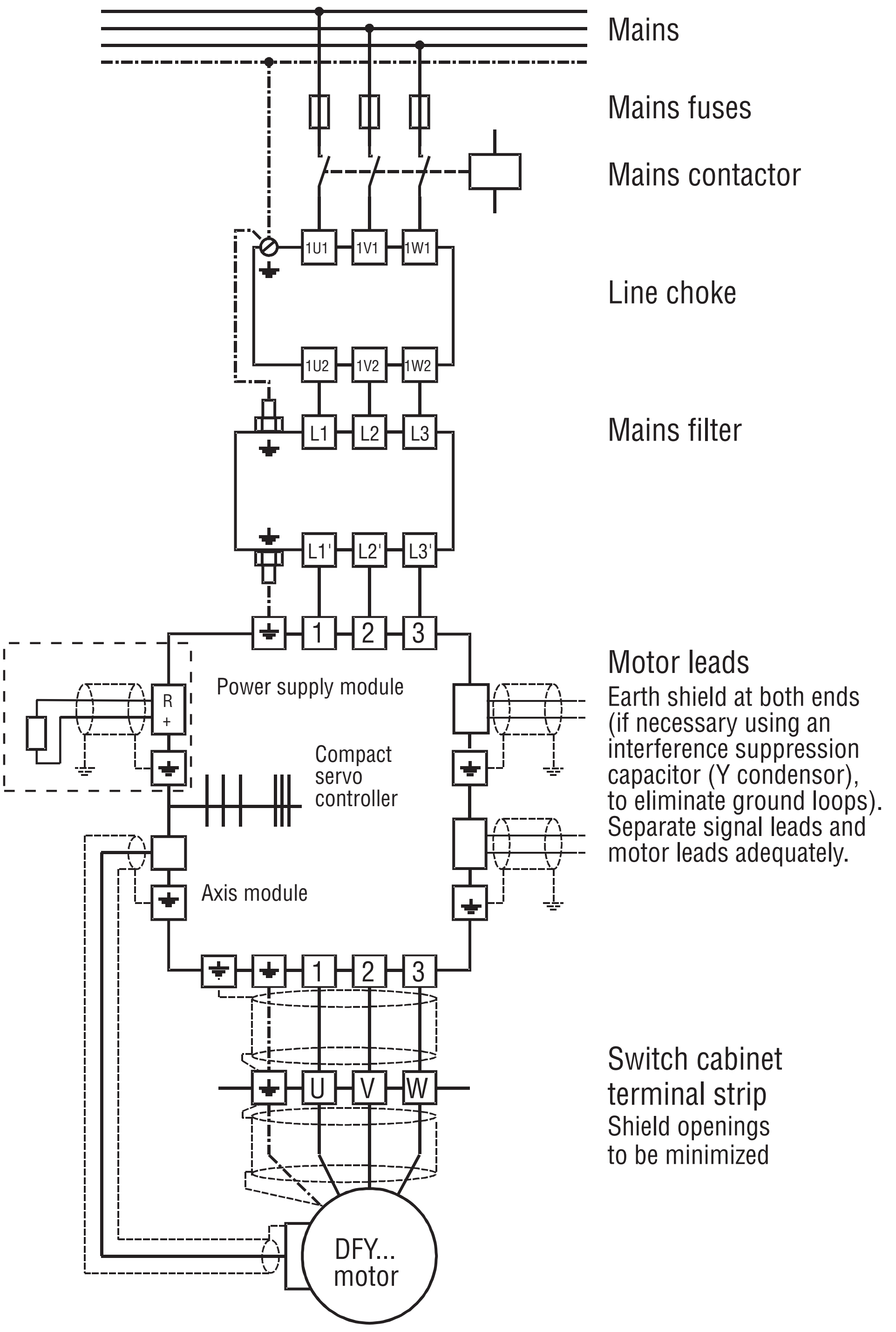
The type of cables and how they are laid is very important in servo drive applications. The cables must be dimensioned to suit the current flowing through them and thus ensure that the voltage drop is kept to the specified value. Refer to the applicable regulations for further information on cable dimensioning.

The laying of the cables, especially when using a cable duct or rack, requires a great deal of care. The effect of EMC will be reduced if power cables and electronic leads are laid separately. Screened cables are excellent at preventing electromagnetic interference in the system.

7.4 Electromagnetic compatibility (EMC)

The EMC of the components of a system and of the system itself is extremely important. The EMC Directive lays down the permitted conditions. This defines not only the levels of emitted interference, but also the immunity to interference. All SEW servo controllers are interference-suppressed, which means they can be used in industrial environments. To suppress interference, the use of screened cables and a mains input filter is recommended.

The resolver lead in particular must be screened. How the screen is to be earthed depends on several factors. For further instructions please refer to the applicable documentation.



Mains

Mains fuses

Mains contactor

Line choke

Mains filter

Motor leads
Earth shield at both ends (if necessary using an interference suppression capacitor (Y condensor), to eliminate ground loops).
Separate signal leads and motor leads adequately.

Switch cabinet terminal strip
Shield openings to be minimized

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Fig. 52: EMC-compliant wiring in residential areas

7.5 Interfaces to the environment

Several channels are available for control of and feedback from the servo controller. Feedback signals from the servo controller are routed to higher-level functional units such as a PLC or an external positioning control. It is important that the applicable interface standards be adhered to.

Interface	Level
Binary inputs	“1" +13V ... **24V** ... 30.2V
Analogue inputs	-10V ... +10V
RS-232	to RS-232 standard
RS-485	to RS-485 standard
Encoder simulation	RS-422 TTL standard
Fieldbus	to the applicable standard (Profibus, INTERBUS-S, CAN bus)

The powerful binary outputs can be used to drive commercial relays or small power contactors. The advantage of a relay driver output is that the electronics need not be exchanged together with the relay when the relay fails.

The inputs are electrically isolated with optocouplers, offering maximum noise immunity. They can be controlled directly from a PLC etc.

The controller parameters can be easily set and commissioned through the standard RS-232 PC interface. The following diagram shows the flexible use of a controller in an industrial environment.

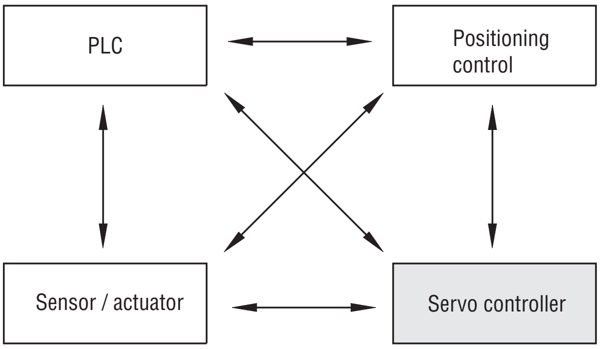


Fig. 53: Interfaces

Digital inputs/outputs:	Freely programmable with specified functions
Analogue inputs:	Setpoint input for speed, torque, maximum current
Analogue outputs:	Output of process values
Serial interface:	RS-232/RS-485 for connection of a PC, process interfacing
Encoder simulation:	Incremental position signal for internal/external position controller
Fieldbus:	Process interfacing

Figure 53 shows possible system configurations as seen from the servo controller:

- The direct link between servo controller and sensor-actuator level (limit switches, pressure marks, sensors etc.) is the simplest type of application. Simple tasks can be handled without connection to a PLC or positioning control.
- With more complex systems there is normally a higher-level control (PLC). Communication is normally via the I/O level of the PLC and the servo controller. The PLC must have an analogue output for analogue setpoint processing. Communication is also possible via serial interface or fieldbus, e.g. for visualization of data, parameter adjustment, process data exchange etc.
  The sensor-actuator level can be connected directly or through the PLC.
- Where positioning functions have to be performed, positioning modules are frequently used as accessory modules to the PLC or as standalone systems. In addition to the connection possibilities listed in point 2, the encoder simulation of the servo controller is generally used to provide the incremental position actual value signal for the positioning module.
- Apart from being integrated into the PLC, the positioning control can also be implemented as option pcb or as software in the servo controller. In this case setpoint input to the servo controller is digital. Connections can be made via the I/O level of the servo controller, a serial interface or the fieldbus.

7.6 Definitions of process interfacing

7.6.1 Classification by drive configuration

- Single-axis applications:
  In terms of control design this application is the least demanding for the higher-level control.
  Typical is the use of a positioning control with digital input/outputs for monitoring the drive.
- Multi-axis applications:
  - point-to-point
  - synchronous operation
  - angular synchronism
  - path control

The working process determines the control complexity in multi-axis applications. The dependence and accuracy of movement of electrically coupled drives are decisive in the choice of a suitable multi-axis control.

7.6.2 Classification by setpoint sources for the speed controller

- Setpoint input without process interfacing (control):

  - internal digital setpoint input in MD_SHELL panel mode (Test/Commissioning).
  - analogue speed or torque control by means of potentiometer.
  - analogue speed control with position or time-dependent setpoint selection.

- Setpoint input with process interfacing:

  - analogue setpoint input by an external positioning control (open-loop/closed-loop).
  - digital setpoint input by internal API/APA 12.
  - digital setpoint input by an external positioning control via fieldbus.

7.6.3 Classification by type and mounting location of the position encoder

When using a positioning control the position actual value must be detected by an encoder. The point of measurement depends on the influence of disturbances, the resolution of the encoder and the required accuracy. Compatibility with the positioning control must also be considered when choosing the encoder. For many applications the encoder simulation integrated in the servo controller is used.

- Position encoder:
  - incremental encoder simulation of the resolver signal
  - external incremental encoder at a working process location (material to be conveyed, conveyor belt, etc.)
  - absolute encoder at the motor

7.7 Ambient conditions

The ambient conditions must be looked at separately for the motor and the servo controller. The maximum ambient temperatures for the motor and the servo controller are:

Motor:	-25°C...40°C	with 100% M_0	max. ϑ = 60°C with 75% M_0
Servo controller	0°C...45°C	with 100% P_N	max. ϑ = 60°C with 55% P_N

For further details of the permissible ambient conditions see the notes on project planning.

7.8 Commissioning and controller optimization

Commissioning and controller optimization are nowadays performed similarly to a PLC, CNC etc., using a PC and the associated software. The software must be simple, clear and user-friendly. In addition, there are operating controls inside the unit.

Prior to commissioning the servo drive system the mounted system components must be compared against the project planning data for correctness.

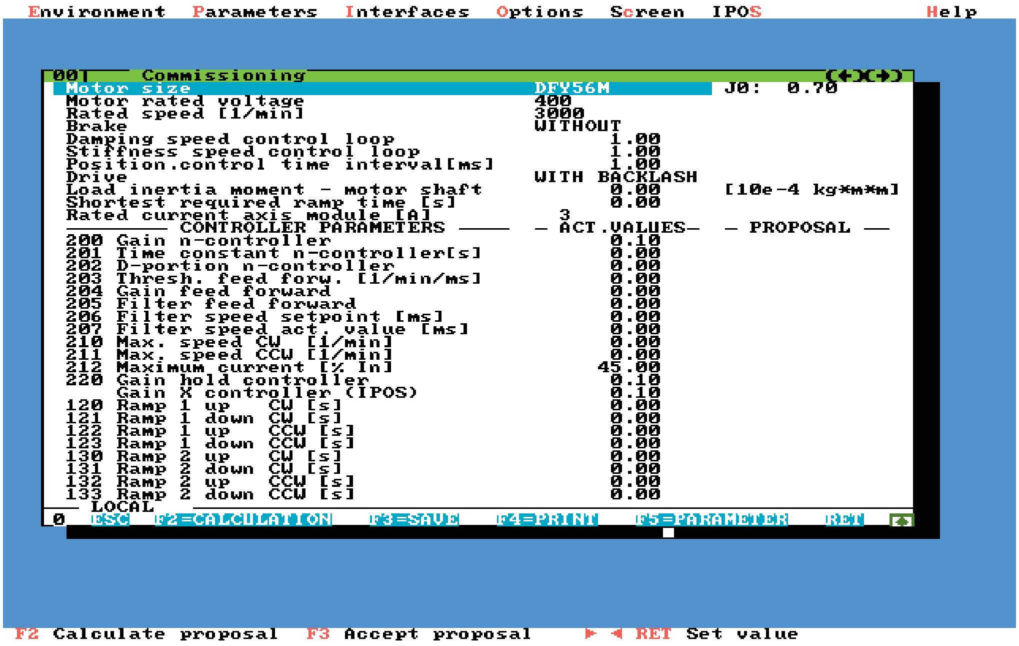
If the cables are laid and wired correctly (screening), commissioning of the drive can be started.

7.8.1 Controller setting with the MD_SHELL user interface

The user interface described here enables the user to carry out a rapid first commissioning. This includes the basic setting of the speed controller, calculated from project-specific data, in the user interface.

- Select the “Commissioning” menu item of the “Parameters” menu
- Enter the requested data
  - motor frame size
  - rated speed
  - brake
  - damping of speed control loop
  - stiffness of the speed control loop
  - positioning control time interval
  - drive with / without backlash
  - load moment of inertia reflected to the motor shaft
  - shortest required ramp time

By pressing the [F2] key all necessary parameters are calculated and the limit values for the given drive set. The drive can be commissioned with the basic setting of the speed controller displayed.



```
[00]    Commissioning                                         (←)(→)
 Motor size                                  DFY56M          J0:   0.70
 Motor rated voltage                         400
 Rated speed [1/min]                         3000
 Brake                                       WITHOUT
 Damping speed control loop                        1.00
 Stiffness speed control loop                      1.00
 Position.control time interval[ms]                1.00
 Drive                                       WITH BACKLASH
 Load inertia moment - motor shaft                 0.00      [10e-4 kg*m*m]
 Shortest required ramp time [s]                   0.00
 Rated current axis module [A]                 3
 ──── CONTROLLER PARAMETERS ────             ─ ACT.VALUES─   ─ PROPOSAL ──
 200 Gain n-controller                             0.10
 201 Time constant n-controller[s]                 0.00
 202 D-portion n-controller                        0.00
 203 Thresh. feed forw. [1/min/ms]                 0.00
 204 Gain feed forward                             0.00
 205 Filter feed forward                           0.00
 206 Filter speed setpoint [ms]                    0.00
 207 Filter speed act. value [ms]                  0.00
 210 Max. speed CW  [1/min]                        0.00
 211 Max. speed CCW [1/min]                        0.00
 212 Maximum current [% In]                       45.00
 220 Gain hold controller                          0.10
     Gain X controller (IPOS)                      0.10
 120 Ramp 1 up   CW [s]                            0.00
 121 Ramp 1 down CW [s]                            0.00
 122 Ramp 1 up   CCW [s]                           0.00
 123 Ramp 1 down CCW [s]                           0.00
 130 Ramp 2 up   CW [s]                            0.00
 131 Ramp 2 down CW [s]                            0.00
 132 Ramp 2 up   CCW [s]                           0.00
 133 Ramp 2 down CCW [s]                           0.00
  LOCAL
0
F2 Calculate proposal   F3 Accept proposal     ► ◄ RET Set value
```

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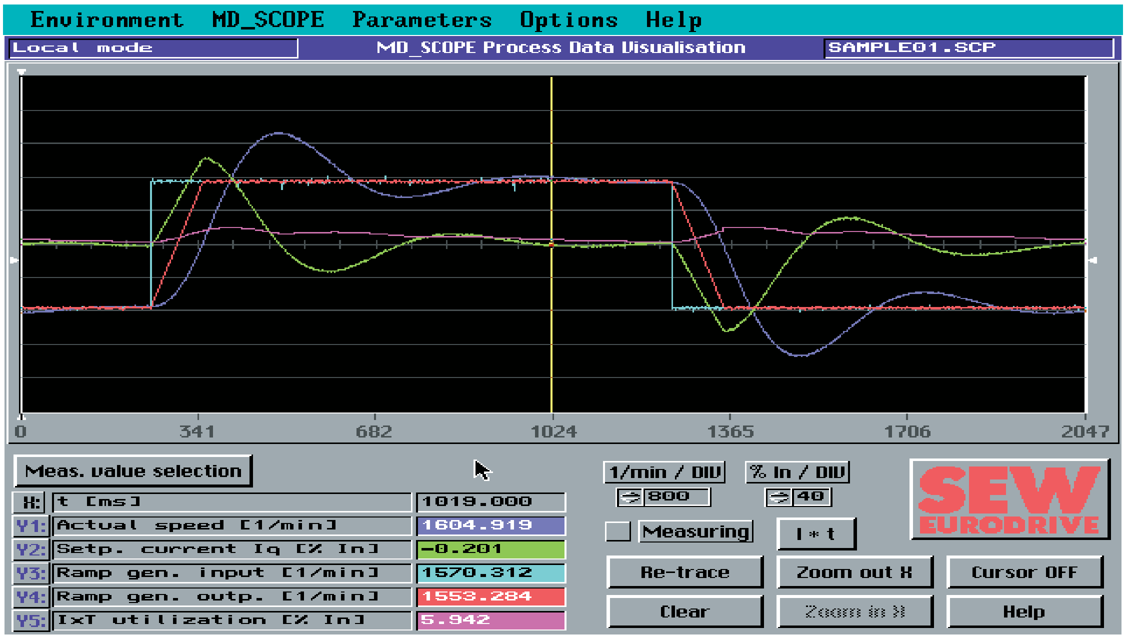
Fig. 54: “Commissioning” menu

The basic setting normally gives satisfactory results, although the following aids are available if further optimization is required:

- Use of the MD_SCOPE software for process data visualization which offers the function of a digital storage oscilloscope. Setpoints and actual values etc. can be displayed on a PC monitor screen as a function of time, they can be stored and printed out. At the same time, control parameters can be changed without having to change to the user interface.

- The control parameters can be optimized without a utility program, using the AIO11 option and an oscilloscope. To do this, the analogue outputs on the option must be programmed accordingly.

7.8.2 Controller optimization using MD_SCOPE



X:	t [ms]	1019.000
Y1:	Actual speed [1/min]	1604.919
Y2:	Setp. current Iq [% In]	-0.201
Y3:	Ramp gen. input [1/min]	1570.312
Y4:	Ramp gen. outp. [1/min]	1553.284
Y5:	IxT utilization [% In]	5.942

1/min / DIV: 800

% In / DIV: 40

☐ Measuring

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Fig. 55: Process data tracing with MD_SCOPE

Fig. 55 shows the trace of the selected measured values (actual speed, current setpoint, ramp generator input and output) for adjustment of the parameters as calculated by the user interface. The drive rapidly attains the setpoint speed, overshoots once, and reaches the setpoint value relatively quickly.

The parameters “Damping” and “Stiffness” allow all parameters of the control loop to be adjusted for smooth control response.

8 Project planning

8.1 Flowchart of servo drive project planning

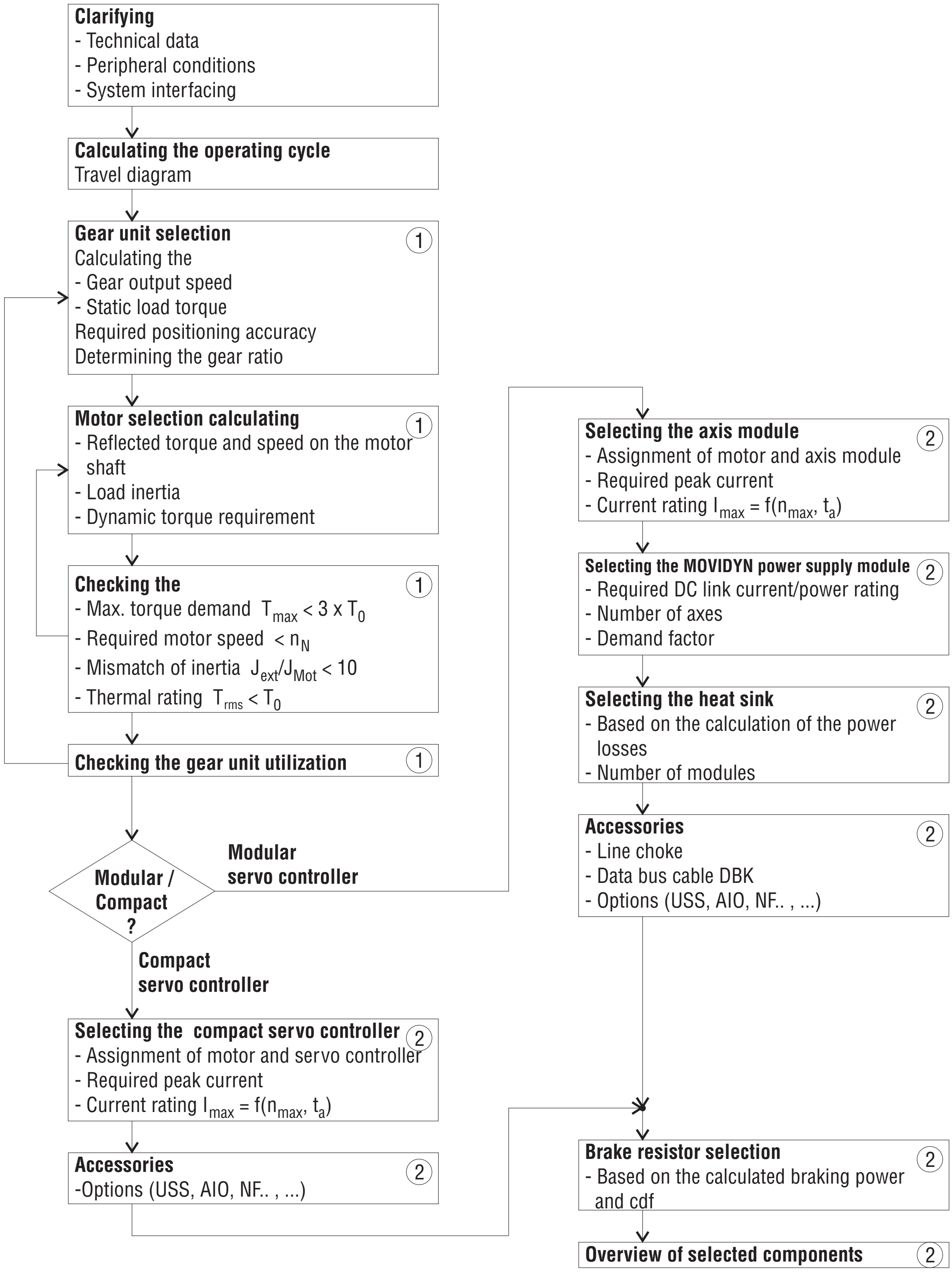

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Fig. 56: Project planning flowchart

8.2 Project planning example

For a three-axis gantry application the servo drives and the appropriate power electronics shall be selected. The axes of the gantry system shall be referred to as X, Y, Z, reflecting their location in space.

X axis

Travel axis driving two toothed belts via a shaft. The toothed belts move the two drive units Y and Z in the plane.

Y axis

Travel axis moving the Z axis via a toothed belt. The direction of travel is at 90° relative to the X axis in the plane.

Z axis

Hoist axis with power transmission by means of a gear rack.

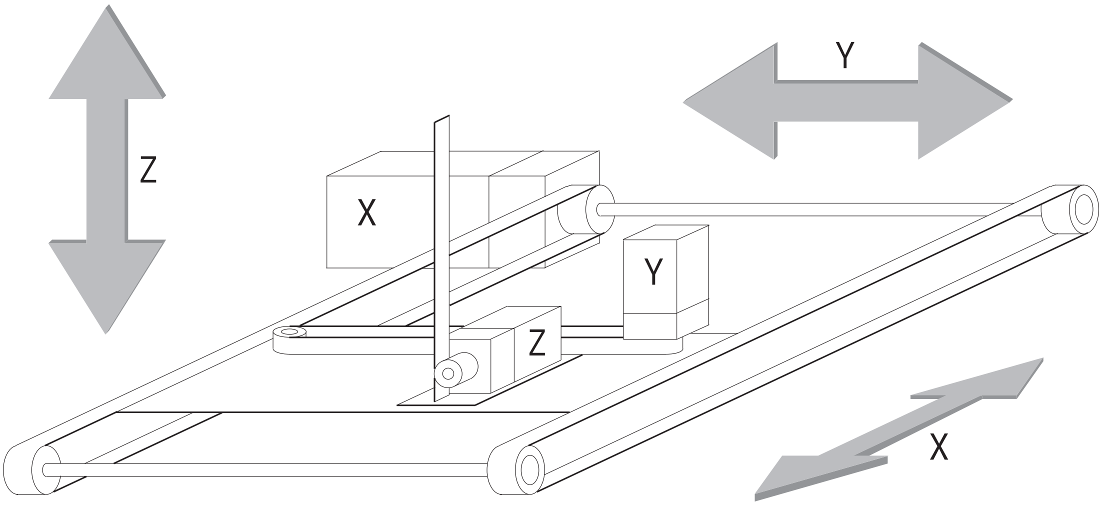

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Fig. 57: Arrangement of the axes

The design calculations shall be done separately for each axis. All calculations are based on linear acceleration and deceleration. Further requirements are the use of modular components and of a braking resistor. Positioning is controlled by a higher-level PLC.

Note:

"*" refers to load data reflected to the drive side.

8.3 Calculating the X axis (travel drive)

Input data

m_L = 453 kg total moved masses
D = 0.175 m belt pulley diameter
μ_L = 0.2 coefficient of friction
s = 2 m travel distance
v_{max} = 2.5 m/s max. traveling velocity
a_{max} = 10 m/s^2 max. acceleration and deceleration
t_Z = 2.1 s cycle time
Δs_1 = ±0.1 mm mechanical accuracy
Δs < ±0.2 mm required overall accuracy
η_L = 0.90 load efficiency

8.3.1 Travel cycle

Before the appropriate drive can be selected, the cycle of motions must first be determined. Since the X axis is a travel axis, it suffices to determine one direction of travel only (1 ... 4).

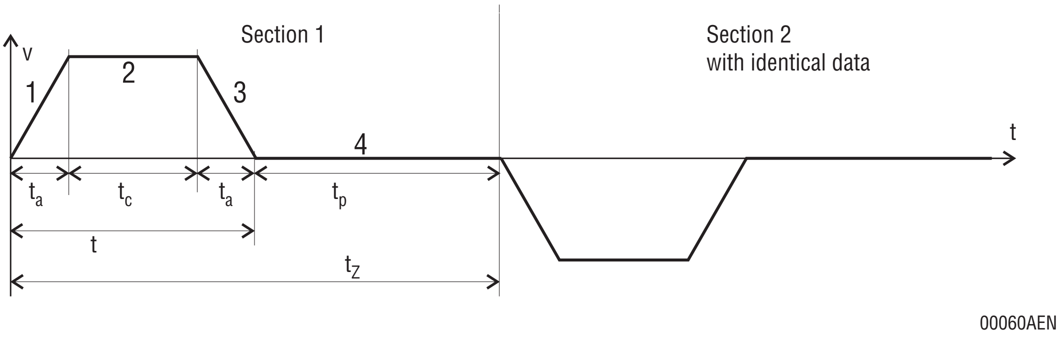

Fig 58: Travel cycle

Acceleration and deceleration time t_a

$$t_a = \frac{v_{max}}{a_{max}} = \frac{2.5\,\frac{m}{s}}{10\,\frac{m}{s^2}} = \underline{\underline{0.25\,s}}$$

Travel time t_c at v_{max} = const.

$$t_c = \frac{s - 2 \cdot \left(\frac{1}{2} a \cdot t_a^{\,2}\right)}{v_{max}} = \frac{2\,m - 10\,\frac{m}{s^2} \cdot (0.25\,s)^2}{2.5\,\frac{m}{s}} = \underline{\underline{0.55\,s}}$$

Overall travel time t and rest period t_p

$$t = 2 \times t_a + t_c = 2 \times 0.25\,s + 0.55\,s = \underline{\underline{1.05\,s}}$$

$$t_p = t_Z - t = 2.1\,s - 1.05\,s = \underline{\underline{1.05\,s}}$$

8.3.2 Output speed, gear ratio ond positioning accuracy

Output speed n

$$n = \frac{v_{max}}{D \cdot \pi} = \frac{2.5\,\frac{m}{s}}{0.175\,m \cdot \pi} = 4.547\,s^{-1} = \underline{\underline{272.8\,min^{-1}}}$$

Gear ratio

In view of the required positioning accuracy a planetary gear unit with an input speed of 3000 min^{-1}

$$i_{setp} = \frac{3000\,min^{-1}}{272.8\,min^{-1}} = 11{,}0 \qquad \text{selected gear ratio } i = 10$$

$$n^* = n \cdot i = 272.8\,min^{-1} \cdot 10 = \underline{\underline{2728\,min^{-1}}}$$

Positioning accuracy (static)

$$\Delta s = \Delta s_G + \Delta s_M + \Delta s_1$$

Δs_G: positioning accuracy derived from gear backlash
Δs_M: positioning accuracy derived from encoder resolution
Δs_1: positioning accuracy derived from mechanical components

$$\Delta s_G = \frac{D \cdot \pi}{360°} \cdot \alpha_G = \frac{0.175\,\text{m} \cdot \pi}{360°} \cdot 0.1° = 0.153\,\text{mm} \quad \rightarrow \quad \pm 0.076\,\text{mm}$$

α_G = 6’ = 0.1° for standard planetary gear units (single - stage), see PSF - Planetary Gear Units Catalogue

$$\Delta s_M = \pm \frac{D \cdot \pi}{p \cdot i} = \pm \frac{0.175\,\text{m} \cdot \pi}{4096 \cdot 10} = \pm 0.013\,\text{mm}$$

p = 4096 pulses per revolution (encoder resolution)

$$\Delta s = (\pm 0.076\,\text{mm}) + (\pm 0.013\,\text{mm}) + (\pm 0.1\,\text{mm}) = \underline{\underline{\pm 0.189\,\text{mm}}} < \pm 0.2\,\text{mm}$$

The positioning accuracy meets the application requirements.

8.3.3 Load torques at the gear output and gear unit selection

Acceleration

$$M_{dyn_1} = m_L \cdot a_{max} \cdot \frac{1}{\eta_L} \cdot \frac{D}{2} = 453\,\text{kg} \cdot 10\,\tfrac{\text{m}}{\text{s}^2} \cdot \frac{1}{0.9} \cdot \frac{0.175\,\text{m}}{2} = \underline{\underline{440.42\,\text{Nm}}}$$

Constant travel, static load

$$M_{stat} = m_L \cdot g \cdot \mu_L \cdot \frac{1}{\eta_L} \cdot \frac{D}{2} = 453\,\text{kg} \cdot 9.81\,\tfrac{\text{m}}{\text{s}^2} \cdot 0.2 \cdot \frac{1}{0.9} \cdot \frac{0.175\,\text{m}}{2} = \underline{\underline{86.41\,\text{Nm}}}$$

Deceleration

$$M_{dyn_2} = m_L \cdot (-a_{max}) \cdot \eta_L \cdot \frac{D}{2} = 453\,\text{kg} \cdot \left(-10\,\tfrac{\text{m}}{\text{s}^2}\right) \cdot 0.9 \cdot \frac{0.175\,\text{m}}{2} = \underline{\underline{-356.74\,\text{Nm}}}$$

Load torques in the travel cycle

Acceleration phase $M_1 = M_{stat} + M_{dyn_1} = 440.42\,\text{Nm} + 86.41\,\text{Nm} = \underline{\underline{526.83\,\text{Nm}}}$

Uniform motion $M_2 = M_{stat} = \underline{\underline{86.41\,\text{Nm}}}$

Deceleration phase $M_3 = M_{stat} + M_{dyn_2} = 86.41\,\text{Nm} - 356.74\,\text{Nm} = \underline{\underline{-270.33\,\text{Nm}}}$

The maximum torque demand M1 determines the required M_{amax} of the gear unit and consequently the gear unit size.

The selected gear unit is a PSF 701, i = 10, M_{amax} = 800 Nm with an “EB10" curved-tooth coupling. The latter was chosen to satisfy the application requirement for separability of motor and gear unit.

8.3.4 Motor-reflected torques and mass moments of inertia

When determining the motor-reflected torques the efficiencies and moments of inertia of both the gear unit and the motor must be taken into account.

Gear unit data (see PSF – Planetary Gear Units Catalogue)

single - stage planetary gear unit	$\eta_G = 0.97$
PSF 701 / EB 10:	$J_G^* = 28.51 \cdot 10^{-4}\,\text{kgm}^2$ (reflected onto the motor shaft)

Load torques in the travel cycle (reflected onto the motor)

Acceleration phase $M_1{}^* = M_1 \cdot \frac{1}{\eta_G \cdot i} = 526.83\,\text{Nm} \cdot \frac{1}{0.97 \cdot 10} = \underline{\underline{54.31\,\text{Nm}}}$

Uniform motion $M_2{}^* = M_2 \cdot \frac{1}{\eta_G \cdot i} = 86.41\,\text{Nm} \cdot \frac{1}{0.97 \cdot 10} = \underline{\underline{8.91\,\text{Nm}}}$

Deceleration phase $M_3{}^* = M_3 \cdot \eta_G \cdot \frac{1}{i} = -270.33\,\text{Nm} \cdot 0.97 \cdot \frac{1}{10} = \underline{\underline{-26.22\,\text{Nm}}}$

Additional torques for the gear moment of inertia reflected to the motor

$$M_{1G}{}^* = \frac{J_G{}^* \cdot 2\pi \cdot n^*}{60\,\frac{s}{min} \cdot t_a \cdot \eta_G} = \frac{28.51 \cdot 10^{-4}\,\text{kgm}^2 \cdot 2\pi \cdot 2728\,\text{min}^{-1}}{60\,\frac{s}{min} \cdot 0.25\,\text{s} \cdot 0.97} = \underline{\underline{3.36\,\text{Nm}}}$$

There is no M_{2G} for M_2 since there is no change in speed.

$$M_{3G}{}^* = \frac{J_G{}^* \cdot 2\pi \cdot n^* \cdot \eta_G}{60\,\frac{s}{min} \cdot t_a} = \frac{28.51 \cdot 10^{-4}\,\text{kgm}^2 \cdot 2\pi \cdot 2728\,\text{min}^{-1} \cdot 0.97}{60\,\frac{s}{min} \cdot 0.25\,\text{s}} = \underline{\underline{-3.16\,\text{Nm}}}$$

Mass moment of inertia of translatory load movement

$$J_L{}^* = m_L \cdot \left(\frac{60\,\frac{s}{min}}{2\pi}\right)^2 \cdot \left(\frac{v_{max}}{n^*}\right)^2 = 453\,\text{kg} \cdot \left(\frac{60\,\frac{s}{min}}{2\pi}\right)^2 \cdot \left(\frac{2.5\,\frac{m}{s}}{2728\,\text{min}^{-1}}\right)^2 = \underline{\underline{0.0347\,\text{kgm}^2}}$$

8.3.5 Motor selection and rms torque

The following conditions must be verified for motor selection:

a) $k_j = \frac{J_{ext}{}^*}{J_{Mot}} < 10$ (mass moment of inertia)

To ensure satisfactory control response the ratio of external moment of inertia to motor moment of inertia should be less than 10.

b) $M_{max}{}^* < 3 \cdot M_0$

The maximum dynamic load on the drive may not exceed three times the motor rated torque.

c) $M_{rms} < M_{perm}$

The rms torque which is effective over the entire travel cycle may not exceed the motor rated torque taking account of the motor characteristic (M_{perm} based on M_0 and motor characteristic).

d) $n^* \approx 0.9\,n_N$

The maximum expected speed should be 90 % of the motor rated speed to provide for a control reserve of approx. 10 %.

Now a motor is selected initially without consideration of the motor moment of inertia. The selection must then be confirmed by way of recalculation using the actual motor moment of inertia.

$$J_{ext}{}^* = J_L{}^* + J_G{}^* = 0.0347\,\text{kgm}^2 + 0.0028\,\text{kgm}^2 = \underline{\underline{0.0375\,\text{kgm}^2}}$$

$$M_{max}{}^* = M_1{}^* + M_{1G}{}^* = 54.31\,\text{Nm} + 3.36\,\text{Nm} = \underline{\underline{57.67\,\text{Nm}}}$$

The initial selection is an estimate. The motor is approximately determined by $M_0 \geq \frac{M_{max}}{2}$.

The choice of this factor requires some experience when configuring the drive.
A factor between 2 and 3 may be chosen.

Selected motor: DFY 112 LB

Rated data:
$n_N = 3000\,\text{min}^{-1}$
$M_0 = 35\,\text{Nm}$
$J_{mot} = 148 \cdot 10^{-4}\,\text{kgm}^2$

Recalculating the motor torques in the travel cycle taking account of the motor moment of inertia

Acceleration phase $M_{1mot} = M_1{}^* + M_{1G}{}^* + \frac{J_{mot} \cdot n^* \cdot 2\pi}{60 \frac{s}{min} \cdot t_a} = 54.31\,Nm + 3.36\,Nm + 16.91\,Nm = \underline{\underline{74.58\,Nm}}$

Uniform motion $M_{2mot} = M_2{}^* = \underline{\underline{8.91\,Nm}}$

Deceleration phase $M_{3mot} = M_3{}^* + M_{3G}{}^* - \frac{J_{mot} \cdot n^* \cdot 2\pi}{60 \frac{s}{min} \cdot t_a} = -26.22\,Nm - 3.16\,Nm - 16.91\,Nm = \underline{\underline{-46.29\,Nm}}$

Rms motor torque and mean motor speed

$$M_{rms} = \sqrt{\frac{1}{t_Z} \cdot \left(M_{1mot}{}^2 \cdot t_a + M_{2mot}{}^2 \cdot t_c + M_{3Mot}{}^2 \cdot t_a\right)}$$

$$= \sqrt{\frac{1}{2.1\,s} \cdot \left[(74.58\,Nm)^2 \cdot 0.25\,s + (8.91\,Nm)^2 \cdot 0.55\,s + (-46.29\,Nm)^2 \cdot 0.25\,s\right]} = \underline{\underline{30.63\,Nm}}$$

$$\bar{n} = \frac{n^* \cdot \left(\frac{1}{2} t_a + t_c + \frac{1}{2} t_a\right)}{t_Z} = n^* \frac{t_a + t_c}{t_Z} = 2728\,min^{-1} \cdot \frac{0.25\,s + 0.55\,s}{2.1\,s} = \underline{\underline{1039\,min^{-1}}}$$

$$cdf\,[\%] = \frac{t_a + t_c + t_a}{t_Z} \cdot 100\,\% = \frac{0.25\,s + 0.55\,s + 0.25\,s}{2.1\,s} \cdot 100\,\% = \underline{\underline{50\,\%}}$$

8.3.6 Checking the selected drive

Geared motor: PSF 701 EB DY 112 LB

Rated data:

$i =$ 10

$M_{amax} =$ 800 Nm

$n_N =$ 3000 min^{-1}

$M_0 =$ 35 Nm

$I_0 =$ 24 A

$J_{mot} =$ $148 \cdot 10^{-4}$ kgm^2

Requirements:

a) $M_{amax} > M_1$

800 Nm > 526.83 Nm met

b) $k_j > 10$

$k_j = \frac{J_{ext}{}^*}{J_{mot}} = \frac{0.0375\,kgm^2}{0.0148\,kgm^2} = \underline{\underline{2.53}}$ met

c) $M_{1mot} < 3 \cdot M_0$

$\frac{M_{1mot}}{M_0} = \frac{74.58\,Nm}{35\,Nm} = \underline{\underline{2.13}}$ met

d) $M_{rms} < M_{perm}$

30 Nm < 32 Nm met

M_{perm} = 32 Nm; (S1 duty) taken from characteristic at n = 1039 min^{-1}

e) $n^* \approx 0.9 \cdot n_N$

$\frac{n^*}{n_N} = \frac{2728\,min^{-1}}{3000\,min^{-1}} = \underline{\underline{0.91}}$ met

All requirements are met.

8.3.7 Selection and design calculation of the servo controller components

The worked example below gives the selection details of an individual drive (single-axis drive). After concluding the design calculations for the X, Y and Z axes, the supply for all three drives together shall be determined in comparison.

Axis module

The axis module must satisfy the following selection criteria:

a) $I_N > \frac{I_{max}}{1.5}$

This condition follows from the axis modules' ability to supply 1.5 times the rated current.

$$I_{max} = \frac{M_{1Mot}}{M_0} \cdot I_0 = \frac{74.58\,Nm}{35\,Nm} \cdot 24\,A = 51.14\,A \qquad \rightarrow \quad I_N > \underline{\underline{34.1\,A}}$$

b) $I_N > \bar{I}$

The current mean value $\bar{I}$ is a measure of the axis modules' thermal load rating.

$$\bar{I} = \frac{I_0}{M_0} \cdot \frac{1}{t_Z} \cdot \left(\left|M_{1mot}\right| \cdot t_a + \left|M_{2mot}\right| \cdot t_c + \left|M_{3mot}\right| \cdot t_a \right)$$

$$\bar{I} = \frac{24\,A}{35\,Nm} \cdot \frac{1}{2.1\,s} \cdot (74.58\,Nm \cdot 0.25\,s + 8.91\,Nm \cdot 0.55\,s + 46.29\,Nm \cdot 0.25\,s) = 11.5\,A \qquad \rightarrow \quad I_N > \underline{\underline{11.5\,A}}$$

c) Checking the combinability of axis module and motor.

Selected axis module: MAS 51A-060-503-00

Rated data: I_N = 60 A
width = 4 TE

Requirements:

a) $I_N > \frac{I_{max}}{1.5}$

60 A > 34.1 A met

b) $I_N > \bar{I}$

60 A > 11.5 A met

c) Combination of MAS 51A-060-503-00 and motor DFY 112 LB (3000 min^{-1}) permissible as per combination table in the catalogue.

Power supply module

The power supply module must satisfy the following selection criteria:

a) $P_{DC\ link\ max} \geq P_{motmax}$

The maximum DC link power rating must be greater than the maximum required power of the drive.

$$P_{motmax} = \frac{n^* \cdot M_{1mot}{}^* \cdot 2\pi}{60\,\frac{s}{min}} = \frac{2728\,min^{-1} \cdot 74.58\,Nm \cdot 2\pi}{60\,\frac{s}{min}} = \underline{\underline{21306\,W}}$$

b) $P_{BRCmax} > P_{Bmax}$

The braking power of the power supply module must be greater than the braking power of the drive.

$$P_{Bmax} = \left|M_{3mot}\right| \cdot n^* \cdot \frac{2\pi}{60\frac{s}{min}} \cdot \eta_L = 46.29\,Nm \cdot 2728\,min^{-1} \cdot \frac{2\pi}{60\frac{s}{min}} \cdot 0.9 = \underline{\underline{11902\,W}}$$

c) $P_{ZN} > \overline{P}$

The DC link power rating must be greater than the mean power of the drive.

$$\overline{P} = \frac{1}{t_Z} \cdot \left(\frac{1}{2} P_{max} \cdot t_a + \frac{M_{2mot} \cdot n^* \cdot 2\pi}{60\frac{s}{min}} \cdot t_c + \frac{1}{2} P_{Bmax} \cdot t_a \right)$$

$$\overline{P} = \frac{1}{2.1s} \cdot \left(\frac{1}{2} \cdot 21306\,W \cdot 0.25\,s + 2545\,W \cdot 0.55\,s + \frac{1}{2} \cdot 11902\,W \cdot 0.25\,s \right) = \underline{\underline{2643\,W}}$$

Selected power supply module: MPB 51A-027-503-00

Rated data:

$P_{DC\ link}$ = 27 kW
$P_{DC\ link\ max}$ = 54 kW
P_{BRCmax} = 38 kW
Width = 4 TE

Requirements:

a) $P_{DC\ link\ max} \geq P_{mot\ max}$
54 kW ≥ 21.3 kW met

b) $P_{BRC\ max} > P_{B\ max}$
38 kW > 11.9 kW met

c) $P_{DC\ link\ N} > \overline{P}$
27 kW > 2.6 kW met

Braking resistor

Braking resistor selection criteria:

a) $P_{N\ cdf} > \overline{P}_{regen}$

The cdf rating of the braking resistor must be greater than the mean regenerative braking power.

$$\overline{P}_{regen} = \frac{P_{Bmax}}{2} = \frac{11902\,W}{2} = \underline{\underline{5951W}}$$

$$\text{cyclic duration factor } cdf_{BW}\,[\%] = \frac{t_a}{t_Z} \cdot 100\,\% = \frac{0.25\,s}{2.1s} \cdot 100\,\% = \underline{\underline{11.9\,\%}}$$

b) Checking the combinability of braking resistor and supply component.

Selected braking resistor: BW 018-015

Rated data:

P_N = ,5 kW
P_N at 12 % cdf = 9 kW

Requirements:

a) $P_{N\ cdf} > \overline{P}_{regen}$
9 kW > 6 kW met

b) braking resistor permissible as per catalogue met

Heat sink

The following criteria must be considered when selecting the heat sink:

a) The total width of all modules added together. Care must be taken to ensure that the modules are not mounted over the joint between two heat sinks.

b) The maximum heat sink temperature ϑ_{KKmax} (80 °C) may not be exceeded (taking account of the ambient temperature).

Required width:	MBP 51A-027-503-00:	4 TE
	MAS 51A-060-503-00:	4 TE

Power losses to be dissipated by the heat sink:

P_{KK} = heat sink rating
P_{VSNT} = power losses of the switch-mode power supply in the power supply module
P_{VL0} = power losses of the power supply module
P_{VLX} = power losses of the axis module
k = number of axis modules
$\bar{I}$ = current mean value

$$P_{KK} = \tfrac{1}{2} P_{VSNT} + P_{VL0} + P_{VLX}$$

$$P_{VSNT} = 12\,W + 13\,W \cdot 1 = 25\,W$$

$$P_{VL0} = 2\,\tfrac{W}{A} \cdot \bar{I} = 2\,\tfrac{W}{A} \cdot 11.5\,A = 23\,W$$

$$P_{VLX} = 14\,\tfrac{W}{A} \cdot \bar{I} = 14\,\tfrac{W}{A} \cdot 11.5\,A = 161\,W$$

$$P_{KK} = \tfrac{1}{2} \cdot 25\,W + 23\,W + 161\,W = \underline{\underline{196.5\,W}}$$

Note: For an explanation of the constants used please refer to the Appendix.

Selected heat sink:	DKS 09	
Rated data:	R_{th} =	0.17 K/W
	Width =	9 TE

Calculating the temperature rise when ambient temperature ϑ_{amb} = 30 °C

$$\Delta\vartheta = R_{th} \cdot P_{KK} = 0.17\,\tfrac{K}{W} \cdot 196.5\,W = \underline{\underline{33.4\,K}}$$

$$\vartheta_{KK} = \vartheta_{amb}\ \Delta\vartheta = (30 + 33.4)\,^\circ C = \underline{\underline{63.4\,^\circ C}}$$

Requirements:

a)	9 TE > 8 TE		met
b)	$\vartheta_{KK} < \vartheta_{KKmax}$;	63.4 °C < 80 °C	met

Data bus cable and line choke

The length of the data bus cable depends on the number of axis modules connected to the power supply module:

1 MPB + 1 MAS → DBK01

The appropriate line choke can be found in the assignment table in the installation and operating instructions.

Power supply module: MPB 51A-027-503-00

Line choke: ND 045-013

Rated data: I_{ND} = 45 A
L_H = 0.1 mH

Overview of selected components

An overview of selected components shall first be given for the single-axis drive; the selection for the complete example with X, Y and Z axes shall be listed at the project planning example.

Geared motor: PSF 701 EB DY 112 LB ($i = 10$; $n_N = 3000^{-1}$; 400 V) EB 10

Axis module: MAS 51A-060-503-00

Power supply module: MPB 51A-027-503-00

Braking resistor: BW 018-015

Heat sink: DKS 09

Line choke: ND 045-013

Data bus cable: DBK01

8.4 Calculating the Y axis (travel drive)

Input data:

m_L = 132 kg total moved masses
D = 0.175 m belt pulley diameter
μ_L = 0.1 coefficient of friction
s = 1 m travel distance
v_{max} = 2.5 m/s max. traveling velocity
a_{max} = 10 m/s^2 max. acceleration and deceleration
t_Z = 1.3 s cycle time
Δs_1 = ± 0.1 mm mechanical accuracy
Δs < ± 0.2 mm required overall accuracy
η_L = 0.90 load efficiency

8.4.1 Travel cycle

Before the appropriate drive can be selected, the cycle of motions must first be determined. Since the Y axis is a travel axis it suffices to determine one direction of travel only (1 ... 4).

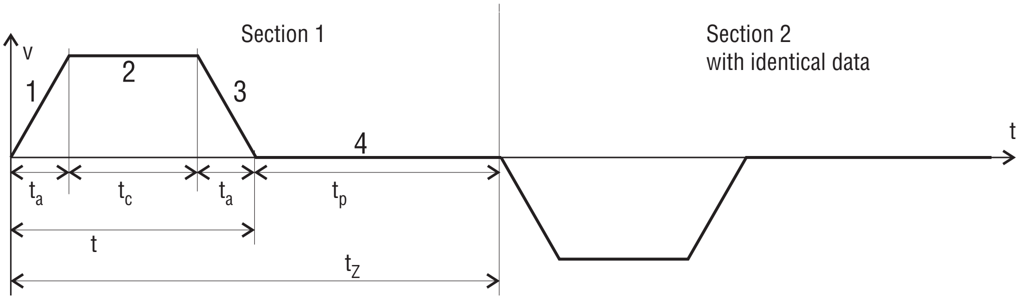

Fig 59: Travel cycle

Acceleration and deceleration t_a

$$t_a = \frac{v_{max}}{a_{max}} = \frac{2.5\,\frac{m}{s}}{10\,\frac{m}{s^2}} = \underline{\underline{0.25\,s}}$$

Travel time t_c at v_{max} = const.

$$t_c = \frac{s - 2 \cdot \left(\frac{1}{2} a \cdot t_a{}^2\right)}{v_{max}} = \frac{1\,m - 10\,\frac{m}{s^2} \cdot (0.25\,s)^2}{2.5\,\frac{m}{s}} = \underline{\underline{0.15\,s}}$$

Overall travel time t and rest period t_p

$$t = 2 \cdot t_a + t_c = 2 \cdot 0.25\,s + 0.15\,s = \underline{\underline{0.65\,s}}$$

$$t_p = t_Z - t = 1.3\,s - 0.65\,s = \underline{\underline{0.65\,s}}$$

8.4.2 Output speed, gear ratio and positioning accuracy

Output speed n

$$n = \frac{v_{max}}{D \cdot \pi} = \frac{2.5\,\frac{m}{s}}{0.175\,m \cdot \pi} = 4.547\,s^{-1} = \underline{\underline{272.8\,min^{-1}}}$$

Gear ratio

In view of the required positioning accuracy a planetary gear unit with an input speed of 3000 min^{-1} is selected.

$$i_{setp}\,\frac{3000\,\text{min}^{-1}}{272.8\,\text{min}^{-1}}=11.0 \qquad \text{selected gear ratio:}\quad i=10$$

$$n^*=n\cdot i=272.8\,\text{min}^{-1}\cdot 10=\underline{\underline{2728\,\text{min}^{-1}}}$$

Positioning accuracy (static)

$$\Delta s=\Delta s_G+\Delta s_M+\Delta s_1$$

Δs_G: positioning accuracy without gear backlash
Δs_M: positioning accuracy derived from encoder resolution
Δs_1: positioning accuracy derived from mechanical components

$$\Delta s_G=\frac{D\cdot\pi}{360^\circ}\cdot\alpha_G=\frac{0.175\,\text{m}\cdot\pi}{360^\circ}\cdot 0.1^\circ=0.153\,\text{mm}\quad\rightarrow\quad\pm 0.076\,\text{mm}$$

α_G = 6' = 0.1° for standard planetary gear units (single-stage)
see PSF – Planetary Gear Units Catalogue

$$\Delta s_M=\pm\frac{D\cdot\pi}{p\cdot i}=\pm\frac{0.175\,\text{m}\cdot\pi}{4096\cdot 10}=\pm 0.013\,\text{mm}$$

p = 4096 pulses per revolution (encoder resolution)

$$\Delta s=(\pm 0.076\,\text{mm})+(\pm 0.013\,\text{mm})+(\pm 0.1\,\text{mm})=\underline{\underline{\pm 0.189\,\text{mm}}}<\pm 0.2\,\text{mm}$$

The positioning accuracy meets the application requirements.

8.4.3 Load torques at the gear output and gear unit selection

Acceleration

$$M_{dyn_1}=m_L\cdot a_{max}\cdot\frac{1}{\eta_L}\cdot\frac{D}{2}=132\,\text{kg}\cdot 10\,\tfrac{\text{m}}{\text{s}^2}\cdot\frac{1}{0.9}\cdot\frac{0.175\,\text{m}}{2}=\underline{\underline{128.33\,\text{Nm}}}$$

Constant travel, static load

$$M_{stat}=m_L\cdot g\cdot\mu_L\cdot\frac{1}{\eta_L}\cdot\frac{D}{2}=132\,\text{kg}\cdot 9.81\,\tfrac{\text{m}}{\text{s}^2}\cdot 0.1\cdot\frac{1}{0.9}\cdot\frac{0.175\,\text{m}}{2}=\underline{\underline{12.59\,\text{Nm}}}$$

Deceleration

$$M_{dyn_2}=m_L\cdot(-a_{max})\cdot\eta_L\cdot\frac{D}{2}=132\,\text{kg}\cdot\left(-10\,\tfrac{\text{m}}{\text{s}^2}\right)\cdot 0.9\cdot\frac{0.175\,\text{m}}{2}=\underline{\underline{-103.95\,\text{Nm}}}$$

Load torques in the travel cycle

Acceleration phase $M_1=M_{stat}+M_{dyn_1}=12.59\,\text{Nm}+128.33\,\text{Nm}=\underline{\underline{140.92\,\text{Nm}}}$

Uniform motion $M_2=M_{stat}=\underline{\underline{12.59\,\text{Nm}}}$

Deceleration phase $M_3=M_{stat}+M_{dyn_2}=12.59\,\text{Nm}-103.95\,\text{Nm}=\underline{\underline{-91.36\,\text{Nm}}}$

The maximum torque demand M_1 determines the required M_{amax} of the gear unit and consequently the gear unit size.

The selected gear unit is a PSF 401, i = 10, M_{amax} = 150 Nm with an “EB09" curved-tooth coupling. The latter was chosen to satisfy the application requirement for separability of motor and gear unit.

8.4.4 Motor-reflected torques and mass moments of inertia

When determining the motor-reflected torques the efficiencies and moments of inertia of both the gear unit and the motor must be taken into account.

Gear unit data (see PSF – Planetary Gear Units Catalogue)

single-stage planetary gear unit: $\eta_G = 0.97$
PSF 401 / EB 09: $J_G^* = 5.76 \cdot 10^{-4}\ \text{kgm}^2$ (reflected to the motor shaft)

Load torques in the travel cycle (reflected to the motor)

Acceleration phase $M_1^* = M_1 \cdot \frac{1}{\eta_G \cdot i} = 140.92\ \text{Nm} \cdot \frac{1}{0.97 \cdot 10} = \underline{\underline{14.53\ \text{Nm}}}$

Uniform motion $M_2^* = M_2 \cdot \frac{1}{\eta_G \cdot i} = 12.59\ \text{Nm} \cdot \frac{1}{0.97 \cdot 10} = \underline{\underline{1.30\ \text{Nm}}}$

Deceleration phase $M_3^* = M_3 \cdot \eta_G \cdot \frac{1}{i} = 91.36\ \text{Nm} \cdot 0.97 \cdot \frac{1}{10} = \underline{\underline{-8.86\ \text{Nm}}}$

Additional torques for the gear unit moment of inertia reflected to the motor

$$M_{1G}^* = \frac{J_G^* \cdot 2\pi \cdot n^*}{60\frac{\text{s}}{\text{min}} \cdot t_a \cdot \eta_G} = \frac{5{,}76 \cdot 10^{-4}\ \text{kgm}^2 \cdot 2\pi \cdot 2728\ \text{min}^{-1}}{60\frac{\text{s}}{\text{min}} \cdot 0.25\ \text{s} \cdot 0.97} = \underline{\underline{0.68\ \text{Nm}}}$$

There is no M_{2G} for M_2 since there is no change in speed.

$$M_{3G}^* = \frac{J_G^* \cdot 2\pi \cdot n^* \cdot \eta_G}{60\frac{\text{s}}{\text{min}} \cdot t_a} = \frac{5.76 \cdot 10^{-4}\ \text{kgm}^2 \cdot 2\pi \cdot 2728\ \text{min}^{-1} \cdot 0.97}{60\frac{\text{s}}{\text{min}} \cdot 0.25\ \text{s}} = \underline{\underline{-0.64\ \text{Nm}}}$$

Mass moment of inertia of translatory load movement

$$J_L^* = m_L \cdot \left(\frac{60\frac{\text{s}}{\text{min}}}{2\pi}\right)^2 \cdot \left(\frac{v_{max}}{n^*}\right)^2 = 132\ \text{kg} \cdot \left(\frac{60\frac{\text{s}}{\text{min}}}{2\pi}\right)^2 \cdot \left(\frac{2.5\frac{\text{m}}{\text{s}}}{2728\ \text{min}^{-1}}\right)^2 = \underline{\underline{0.0101\text{kgm}^2}}$$

8.4.5 Motor selection and rms torque

The following conditions must be verified for motor selection:

a) $k_j = \frac{J_{ext}^*}{J_{mot}} < 10$ (mass moment of inertia)

To ensure satisfactory control response the ratio of external moment of inertia to motor moment of inertia should be less than 10.

b) $M_{max}^* < 3 \cdot M_0$

The maximum dynamic load on the drive may not exceed three times the motor rated torque.

c) $M_{rms} < M_{perm}$

The rms which is effective over the entire travel cycle may not exceed the motor rated torque taking account of the motor characteristic (M_{perm} based M_0 and motor characteristic).

d) $n^* \approx 0.9\ n_N$

The maximum expected speed should be 90 % of the motor rated speed to provide for a control reserve of approx. 10 %.

Now a motor is selected initially without taking account of the motor moment of inertia. The selection must then be confirmed by way of recalculation using the actual motor moment of inertia.

$$J_{ext}^* = J_L^* + J_G^* = 0.0101\text{kgm}^2 + 0.0006\ \text{kgm}^2 = \underline{\underline{0.0107\ \text{kgm}^2}}$$

$$M_{max}^* = M_1^* + M_{1G}^* = 14.53\ \text{Nm} + 0.68\ \text{Nm} = \underline{\underline{15.21\text{Nm}}}$$

Selected motor: DFY 90 MB

Rated data:
$n_N = 3000\ \text{min}^{-1}$
$M_0 = 12\ \text{Nm}$
$J_{mot} = 24.1 \cdot 10^{-4}\ \text{kgm}^2$

Recalculating the motor torques in the travel cycle taking account of the motor moment of inertia

Acceleration phase $M_{1mot} = M_1{}^* + M_{1G}{}^* + \dfrac{J_{mot} \cdot n^* \cdot 2\pi}{60 \frac{s}{min} \cdot t_a} = 14.53\,\text{Nm} + 0.68\,\text{Nm} + 2.75\,\text{Nm} = \underline{\underline{17.96\,\text{Nm}}}$

Uniform motion $M_{2mot} = M_2{}^* = \underline{\underline{1.30\,\text{Nm}}}$

Deceleration phase $M_{3mot} = M_3{}^* + M_{3G}{}^* + \dfrac{J_{Mot} \cdot n^* \cdot 2\pi}{60 \frac{s}{min} \cdot t_a} = -8.86\,\text{Nm} - 0.64\,\text{Nm} - 2.75\,\text{Nm} = \underline{\underline{-12.25\,\text{Nm}}}$

Rms motor torque and mean motor speed

$$M_{rms} = \sqrt{\frac{1}{t_Z} \cdot \left(M_{1mot}{}^2 \cdot t_a + M_{2mot}{}^2 \cdot t_c + M_{3mot}{}^2 \cdot t_a\right)}$$

$$= \sqrt{\frac{1}{1.3\,\text{s}} \cdot \left[(17.96\,\text{Nm})^2 \cdot 0.25\,\text{s} + (1.30\,\text{Nm})^2 \cdot 0.15\,\text{s} + (-12.25\,\text{Nm})^2 \cdot 0.25\,\text{s}\right]} = \underline{\underline{9.54\,\text{Nm}}}$$

$$\overline{n} = \frac{n^* \cdot \left(\frac{1}{2} t_a + n^* \cdot t_c + \frac{1}{2} t_a\right)}{t_Z} = n^* \cdot \frac{t_a + t_c}{t_Z} = 2728\,\text{min}^{-1} \cdot \frac{0.25\,\text{s} + 0.15\,\text{s}}{1.3\,\text{s}} = \underline{\underline{839\,\text{min}^{-1}}}$$

$$\text{cdf}\,[\%] = \frac{t_a + t_c + t_a}{t_Z} \cdot 100\,\% = \frac{0.25\,\text{s} + 0.15\,\text{s} + 0.25\,\text{s}}{1.3\,\text{s}} \cdot 100\,\% = \underline{\underline{50\,\%}}$$

8.4.6 Checking the selected drive

Geared motor: PSF 401 EB09 DY 90 MB

Rated data
$i = 10$
$M_{amax} = 150\ \text{Nm}$
$n_N = 3000\ \text{min}^{-1}$
$M_0 = 12\ \text{Nm}$
$I_0 = 7.9\ \text{A}$
$J_{mot} = 24.1 \cdot 10^{-4}\ \text{kgm}^2$

Requirements:

a) $M_{amax} > M_1$
150 Nm > 140.92 Nm met

b) $k_j < 10$

$k_j = \dfrac{J_{ext}{}^*}{J_{mot}} = \dfrac{0.0107\,\text{kgm}^2}{0.00241\,\text{kgm}^2} = \underline{\underline{4.44}}$ met

c) $M_{1mot} < 3 \cdot M_0$

$\dfrac{M_{1mot}}{M_0} = \dfrac{17.96\,\text{Nm}}{12\,\text{Nm}} = \underline{\underline{1.50}}$ met

d) $M_{rms} < M_{perm}$
9.54 Nm < 12 Nm met
M_{perm} =12 Nm; (S1 duty) taken from characteristic at $n = 840\ \text{min}^{-1}$

e) $n^* \approx 0.9 \cdot n_N$

$\dfrac{n^*}{n_N} = \dfrac{2728\,\text{min}^{-1}}{3000\,\text{min}^{-1}} = \underline{\underline{0.91}}$ met

All requirements are met.

8.4.7 Selection and design calculation of the servo controller components

At this point only the required axis module shall still be determined. For the supply module only the applicable criteria will be specified. The power supply module will then be determined jointly for all three axes.

Axis module

The axis module must satisfy the following selection criteria:

a) $I_N > \frac{I_{max}}{1.5}$

This condition follows from the axis modules' ability to supply 1.5 times the rated current.

$$I_{max} = \frac{M_{1mot}}{M_0} \cdot I_0 = \frac{17.96\,Nm}{12\,Nm} \cdot 7.9\,A = 11.82\,A \qquad \rightarrow \quad I_N > \underline{\underline{7.88\,A}}$$

b) $I_N > \bar{I}$

The current mean value $\bar{I}$ is a measure of the axis modules' thermal load rating.

$$\bar{I} = \frac{I_0}{M_0} \cdot \frac{1}{t_Z} \cdot \left(\left|M_{1mot}\right| \cdot t_a + \left|M_{2mot}\right| \cdot t_c + \left|M_{3mot}\right| \cdot t_a\right)$$

$$\bar{I} = \frac{7.9\,A}{12\,Nm} \cdot \frac{1}{1.3\,s} \cdot (17.96\,Nm \cdot 0.25\,s + 1.30\,Nm \cdot 0.15\,s + 12.25\,Nm \cdot 0.25\,s) = 3.92\,A \qquad \rightarrow \quad I_N > \underline{\underline{3.92\,A}}$$

c) Checking the combinability of axis module and motor.

Selected axis module: MAS 51A-010-503-00

Rated data: $I_N =$ 10 A
width = 2 TE

Requirements:

a) $I_N > \frac{I_{max}}{1.5}$

10 A > 7.88 A met

b) $I_N > \bar{I}$

10 A > 3.92 A met

c) Combination of MAS 51A-010-503-00 and motor DFY 90 MB (3000 min^{-1}) permissible as per combination table in the catalogue.

Power supply module

The power supply module must satisfy the following selection criteria:

a) $P_{Zmax} \geq P_{motmax}$

The maximum DC link power rating must be greater than the maximum required power of the drive.

$$P_{motmax} = \frac{n^* \cdot M_{2Mot} \cdot 2\pi}{60 \frac{s}{min}} = \frac{2728\,min^{-1} \cdot 17.96\,Nm \cdot 2\pi}{60 \frac{s}{min}} = \underline{\underline{5131\,W}}$$

b) $P_{BRCmax} > P_{Bmax}$

The braking power of the power supply module must be greater than the braking power of the drive.

$$P_{Bmax} = n^* \cdot \left|M_{3mot}\right| \cdot \frac{2\pi}{60\,\frac{s}{min}} \cdot \eta_L = 2728\,\text{min}^{-1} \cdot 12.25\,\text{Nm} \cdot \frac{2\pi}{60\,\frac{s}{min}} \cdot 0.9 = \underline{\underline{3150\,\text{W}}}$$

c) $P_{DC\ link\ N} > \overline{P}$

The DC link power rating must be greater than the mean power of the drive.

$$\overline{P} = \frac{1}{t_Z} \cdot \left(\tfrac{1}{2} P_{max} \cdot t_a + \frac{M_{2mot} \cdot n^* \cdot 2\pi}{60\,\frac{s}{min}} \cdot t_c + \tfrac{1}{2} P_{Bmax} \cdot t_a \right)$$

$$\overline{P} = \frac{1}{1.3\,\text{s}} \cdot \left(\tfrac{1}{2} \cdot 5131\,\text{W} \cdot 0.25\,\text{s} + 371.4\,\text{W} \cdot 0.15\,\text{s} + \tfrac{1}{2} \cdot 3150\,\text{W} \cdot 0.25\,\text{s} \right) = \underline{\underline{839\,\text{W}}}$$

Braking resistor duty cycle

$$cdf_{BW}\,[\%] = \frac{t_a}{t_Z} \cdot 100\,\% = \frac{0.25\,\text{s}}{1.3\,\text{s}} \cdot 100\,\% = \underline{\underline{19.23\,\%}}$$

Normally the selection of power supply module, braking resistor, heat sink and line choke would follow at this point. Since these components shall be selected though for a multi-axis application with the MOVIDYN modular servo controller these components will only be selected after the design calculations for the Y, Y and Z axis have been completed.

8.5 Calculating the Z axis (hoist)

Input data:

m_L = 40 kg total moved masses (without counterweight)
D = 0.05 m drive wheel diameter
η_L = 1 coefficient of friction (negligible friction)
s = 1 m travel distance
V_{max} = 1.9 m/s max. travel velocity
a_{max} = 10 m/s^2 max. acceleration and deceleration
t_Z = 2.8 s cycle time for lifting and lowering
Δs_1 = ± 0.1 mm mechanical accuracy
Δs = ± 0.2 mm required overall accuracy
η_L = 0.90 load efficiency

8.5.1 Travel cycle

Before the appropriate drive can be selected the cycle of motions must first be determined

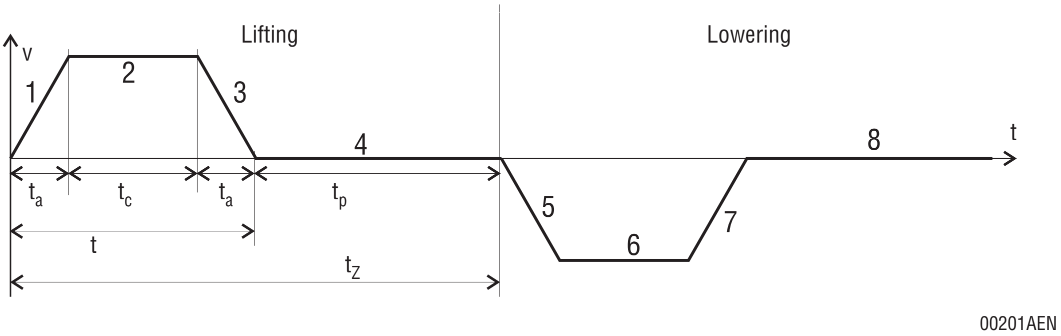

Fig. 60: Travel cycle

Acceleration and deceleration time t_a

$$t_a = \frac{v_{max}}{a_{max}} = \frac{1.9\,\frac{m}{s}}{10\,\frac{m}{s^2}} = \underline{\underline{0.19\,s}}$$

Travel time t_c at v_{max} = const.

$$t_c = \frac{s - 2 \cdot \left(\frac{1}{2}\,a \cdot t_a^{\,2}\right)}{v_{max}} = \frac{1\,m - 10\,\frac{m}{s^2} \cdot (0.19\,s)^2}{1.9\,\frac{m}{s}} = \underline{\underline{0.336\,s}}$$

Overall travel time t and rest period t_p

$$t = 2 \cdot t_a + t_c = 2 \cdot 0.19\,s + 0.336\,s = \underline{\underline{0.716\,s}}$$

$$t_p = t_Z - t = 2.8\,s - 0.716\,s = \underline{\underline{2.084\,s}}$$

8.5.2 Output speed, gear ratio and positioning accuracy

Output speed n

$$n = \frac{v_{max}}{D \cdot \pi} = \frac{1.9\,\frac{m}{s}}{0.05\,m \cdot \pi} = 12.10\,s^{-1} = \underline{\underline{725.7\,min^{-1}}}$$

Gear ratio

In view of the required positioning accuracy a planetary gear unit with an input speed of $3000\ \text{min}^{-1}$ is selected.

$$i_{setp} = \frac{3000\,\text{min}^{-1}}{725.7\,\text{min}^{-1}} = 4.1 \qquad \text{select gear ratio:}\quad i = 4$$

$$n^* = n \cdot i = 725.7\,\text{min}^{-1} \cdot 4 = \underline{\underline{2903\,\text{min}^{-1}}}$$

Positioning accuracy (static)

$$\Delta s = \Delta s_G + \Delta s_M + \Delta s_1$$

Δs_G: positioning derived from gear backlash
Δs_M: positioning accuracy derived from encoder resolution
Δs_1: positioning accuracy derived from mechanical components

$$\Delta s_G = \frac{D \cdot \pi}{360^\circ} \cdot \alpha_G = \frac{0.05\,\text{m} \cdot \pi}{360^\circ} \cdot 0.1^\circ = 0.044\,\text{mm} \quad \rightarrow \quad \pm 0.022\,\text{mm}$$

α_G = 6' = 0.1° for standard planetary gear units (single-stage)
see PSF – Planetary Gear Units Catalogue

$$\Delta s_M = \pm \frac{D \cdot \pi}{p \cdot i} = \pm \frac{0.05\,\text{m} \cdot \pi}{4096 \cdot 4} = \pm 0.010\,\text{mm}$$

p = 4096 pulses per revolution (encoder resolution)

$$\Delta s = (\pm 0.022\,\text{mm}) + (\pm 0.010\,\text{mm}) + (\pm 0.1\,\text{mm}) = \underline{\underline{\pm 0.132\,\text{mm}}} < \pm 0.2\,\text{mm}$$

The positioning accuracy meets the application requirements.

8.5.3 Load torques at the gear output and gear unit selection

Constant travel, lifting

$$M_{stat_1} = m_L \cdot g \cdot \frac{1}{\eta_L} \cdot \frac{D}{2} = 40\,\text{kg} \cdot 9.81\,\tfrac{\text{m}}{\text{s}^2} \cdot \frac{1}{0.9} \cdot \frac{0.05\,\text{m}}{2} = \underline{\underline{10.90\,\text{Nm}}}$$

Constant travel, lowering

$$M_{stat_2} = m_L \cdot g \cdot \eta_L \cdot \frac{D}{2} = 40\,\text{kg} \cdot 9.81\,\tfrac{\text{m}}{\text{s}^2} \cdot 0.9 \cdot \frac{0.05\,\text{m}}{2} = \underline{\underline{8.83\,\text{Nm}}}$$

Acceleration

$$M_{dyn_1} = m_L \cdot a_{max} \cdot \frac{1}{\eta_L} \cdot \frac{D}{2} = 40\,\text{kg} \cdot 10\,\tfrac{\text{m}}{\text{s}^2} \cdot \frac{1}{0.9} \cdot \frac{0.05\,\text{m}}{2} = \underline{\underline{11.11\text{Nm}}}$$

Deceleration

$$M_{dyn_2} = m_L \cdot (-a_{max}) \cdot \eta_L \cdot \frac{D}{2} = 40\,\text{kg} \cdot \left(-10\,\tfrac{\text{m}}{\text{s}^2}\right) \cdot 0.9 \cdot \frac{0.05\,\text{m}}{2} = \underline{\underline{-9.00\,\text{Nm}}}$$

Load torques in the travel cycle

Acceleration phase
Lifting

$$M_1 = M_{dyn_1} + M_{stat_1} = 11.11\,\text{Nm} + 10.90\,\text{Nm} = \underline{\underline{22.01\,\text{Nm}}}$$

Uniform motion
Lifting

$$M_2 = M_{stat_1} = \underline{\underline{10.90\,\text{Nm}}}$$

Deceleration phase
Lifting

$$M_3 = M_{dyn_2} + M_{stat_1} = -9.00\,\text{Nm} + 10.90\,\text{Nm} = \underline{\underline{1.90\,\text{Nm}}}$$

Acceleration phase
Lowering

$$M_5 = M_{dyn_1} - M_{stat_2} = 11.11\,\text{Nm} - 8.83\,\text{Nm} = \underline{\underline{2.28\,\text{Nm}}}$$

Uniform motion
Lowering

$$M_6 = -M_{stat_2} = \underline{\underline{-8.83\,\text{Nm}}}$$

Deceleration phase
Lowering

$$M_7 = M_{dyn_2} - M_{stat_2} = -9.00\,\text{Nm} - 8.83\,\text{Nm} = \underline{\underline{-17.83\,\text{Nm}}}$$

The maximum torque M_1 determines the required M_{amax} of the gear unit and consequently the gear size.

The selected gear unit is a PSF 301, i = 4, M_{amax} = 80 Nm with an “EB04” curved-tooth coupling. The latter was chosen to satisfy the requirement for separability of motor and gear unit.

8.5.4 Motor-reflected torques and mass moments of inertia

When determining the motor reflected torques, the efficiencies and moments of inertia of both the gear unit and the motor must be taken into account.

Gear unit data (see PSF – Planetary Gear Units Catalogue)

single-stage planetary gear unit:	$\eta_G = 0{,}97$
PSF 301 / EB04	$J_G{}^* = 2.3 \cdot 10^{-4}\,\text{kgm}^2$ (reflected to the motor shaft)

Load torques in the travel cycle (reflected to the motor)

Acceleration phase
Lifting

$$M_1{}^* = M_1 \cdot \frac{1}{\eta_G \cdot i} = 22.01\,\text{Nm} \cdot \frac{1}{0.97 \cdot 4} = \underline{\underline{5.67\,\text{Nm}}}$$

Uniform motion
Lifting

$$M_2{}^* = M_2 \cdot \frac{1}{\eta_G \cdot i} = 10.90\,\text{Nm} \cdot \frac{1}{0.97 \cdot 4} = \underline{\underline{2.81\,\text{Nm}}}$$

Deceleration phase
Lifting

$$M_3{}^* = M_3 \cdot \frac{1}{\eta_G \cdot i} = 1.90\,\text{Nm} \cdot \frac{1}{0.97 \cdot 4} = \underline{\underline{0.49\,\text{Nm}}}$$

Standstill

$$M_4{}^* = M_2 \cdot \frac{1}{i} = 10.90\,\text{Nm} \cdot \frac{1}{4} = \underline{\underline{2.73\,\text{Nm}}}$$

Acceleration phase
Lowering

$$M_5{}^* = M_5 \cdot \frac{1}{\eta_G \cdot i} = 2.28\,\text{Nm} \cdot \frac{1}{0.97 \cdot 4} = \underline{\underline{0.59\,\text{Nm}}}$$

Uniform motion
Lowering

$$M_6{}^* = M_6 \cdot \frac{\eta_G}{i} = -8.83\,\text{Nm} \cdot \frac{0.97}{4} = \underline{\underline{-2.14\,\text{Nm}}}$$

Deceration phase
Lowering

$$M_7{}^* = M_7 \cdot \frac{\eta_G}{i} = -17.83\,\text{Nm} \cdot \frac{0.97}{4} = \underline{\underline{-4.32\,\text{Nm}}}$$

Standstill

$$M_8{}^* = M_2 \cdot \frac{1}{i} = 10.90\,\text{Nm} \cdot \frac{1}{4} = \underline{\underline{2.73\,\text{Nm}}}$$

Additional torques for the gear unit moment of inertia reflected to the motor

$$M_{1G}{}^* = \frac{J_G{}^* \cdot 2\pi \cdot n^*}{60\,\frac{s}{min} \cdot t_a \cdot \eta_G} = \frac{2.3 \cdot 10^{-4}\,\text{kgm}^2 \cdot 2\pi \cdot 2903\,\text{min}^{-1}}{60\,\frac{s}{min} \cdot 0.19\,\text{s} \cdot 0.97} = \underline{\underline{0.38\,\text{Nm}}} \qquad \text{(drive motoring)}$$

There is no M_{2G} for M_2 since there is no change in speed.

$$M_{3G}{}^* = \frac{J_G{}^* \cdot 2\pi \cdot n^* \cdot \eta_G}{60\,\frac{s}{min} \cdot t_a} = \frac{2.3 \cdot 10^{-4}\,\text{kgm}^2 \cdot 2\pi \cdot 2903\,\text{min}^{-1} \cdot 0.97}{60\,\frac{s}{min} \cdot 0.19\,\text{s}} = \underline{\underline{-0.36\,\text{Nm}}} \qquad \text{(drive regenerating)}$$

Mass moment of inertia of translatory load movement

$$J_L{}^* = m_L \cdot \left(\frac{60\,\frac{s}{min}}{2\pi}\right)^2 \cdot \left(\frac{v_{max}}{n^*}\right)^2 = 40\,kg \cdot \left(\frac{60\,\frac{s}{min}}{2\pi}\right)^2 \cdot \left(\frac{1.9\,\frac{m}{s}}{2903\,min^{-1}}\right)^2 = \underline{\underline{0.00156\,kgm^2}}$$

8.5.5 Motor selection and rms torque

The following conditions must be verified for motor selection:

a) $k_j = \frac{J_{ext}{}^*}{J_{Mot}} < 10$ (mass moment of inertia)

To ensure satisfactory control response the ratio of external moment of inertia to motor moment of inertia should be less than 10.

b) $M_{max}{}^* < 3 \cdot M_0$

The maximum dynamic load on the drive may not exceed three times the motor rated torque.

c) $M_{rms} < M_{perm}$

The rms torque which is effective over the entire travel cycle may not exceed the motor rated torque taking account of the motor characteristic (M_{perm} based on M_0 and motor characteristic).

d) $n^* \approx 0.9\ n_N$

The maximum expected speed should be 90 % of the motor rated speed to provide for a control reserve of approx. 10 %

Now a motor is selected without taking account of the motor moment of inertia. The selection must then be confirmed by way of recalculation using the actual motor moment of inertia.

$$J_{ext}{}^* = J_L{}^* + J_G{}^* = 0.00156\,kgm^2 + 0.00023\,kgm^2 = \underline{\underline{0.00179\,kgm^2}}$$

$$M_{max}{}^* = M_1{}^* + M_{1G}{}^* = 5.67\,Nm + 0.38\,Nm = \underline{\underline{6.05\,Nm}}$$

The initial selection is an estimate. The motor is approximately determined by $M_0 \geq \frac{M_{max}}{2}$

The choice of this factor requires some experience when configuring the drive.
A factor between 2 and 3 may be chosen.

Selected motor: DFY 71 MLB

Related data:
n_N = 3000 min^{-1}
M_0 = 5 Nm
J_{mot} = 0.000831 kgm^2

Recalculating the motor torques in the travel cycle taking account of the motor moment inertia

$$M_{add\ mot} = \frac{J_{mot} \cdot n^* \cdot 2\pi}{60\,\frac{s}{min} \cdot t_a} = \frac{0.000831\,kgm^2 \cdot 2903\,min^{-1} \cdot 2p}{60\,\frac{s}{min} \cdot t_a} = \underline{\underline{1.33\,Nm}}$$

Acceleration phase
Lifting

$$M_{1mot} = M_1{}^* + M_{1G}{}^* + M_{add\ mot} = 5.67\,Nm + 0.38\,Nm + 1.33\,Nm = \underline{\underline{7.38\,Nm}}$$

Uniform travel
Lifting

$$M_{2mot} = M_2{}^* = \underline{\underline{2.81 Nm}}$$

Deceleration phase
Lifting

$$M_{3mot} = M_3{}^* - M_{3G}{}^* - M_{add\ mot} = 0.49\,Nm - 0.36\,Nm - 1.33\,Nm = \underline{\underline{1.20\,Nm}}$$

Standstill

$$M_{4mot} = M_4{}^* = \underline{\underline{2.73\,Nm}}$$

Acceleration phase Lowering	$M_{5mot} = M_5{}^* + M_{1G}{}^* + M_{add\ mot} = 0.59\,\text{Nm} + 0.38\,\text{Nm} + 1.33\,\text{Nm} = \underline{\underline{2.30\,\text{Nm}}}$
Uniform motion Lowering	$M_{6mot} = M_6{}^* = \underline{\underline{-2.14\,\text{Nm}}}$
Deceleration phase Lowering	$M_{7mot} = M_7{}^* - M_{3G}{}^* - M_{add\ mot} = -4.32\,\text{Nm} - 0.36\,\text{Nm} - 1.33\,\text{Nm} = \underline{\underline{-6.01\,\text{Nm}}}$
Standstill	$M_{8mot} = M_8{}^* = \underline{\underline{2.73\,\text{Nm}}}$

Rms motor torque and mean motor speed

$$M_{rms} = \sqrt{\frac{1}{t_Z} \cdot \left(M_{1mot}{}^2 \cdot t_a + M_{2mot}{}^2 \cdot t_c + M_{3mot}{}^2 \cdot t_a + M_{4mot}{}^2 \cdot t_p + M_{5mot}{}^2 \cdot t_a + M_{6mot}{}^2 \cdot t_c + M_{7mot}{}^2 \cdot t_a + M_{8mot}{}^2 \cdot t_p\right)}$$

$$M_{rms} = \sqrt{\frac{1}{2.8\,\text{s}} \cdot \left[\left(7.38^2 + 1.20^2 + 2.30^2 + 6.01^2\right) \cdot 0.19 + \left(2.81^2 + 2.14^2\right) \cdot 0.336 + \left(2.73^2 + 2.73^2\right) \cdot 0.684\right] \text{N}^2\text{m}^2\text{s}} = \underline{\underline{3.43\,\text{Nm}}}$$

$$\bar{n} = \frac{2 \cdot (n^* \cdot t_a + n^* \cdot t_c)}{t_Z} = \frac{2 \cdot \left(2903\,\text{min}^{-1} \cdot 0.19\,\text{s} + 2903\,\text{min}^{-1} \cdot 0.336\,\text{s}\right)}{2.8\,\text{s}} = \underline{\underline{1091\,\text{min}^{-1}}}$$

$$\text{cdf}\,[\%] = \frac{t_a + t_c + t_a}{t_Z} \cdot 100\,\% = \frac{0.19\,\text{s} + 0.336\,\text{s} + 0.19\,\text{s}}{2.8\,\text{s}} \cdot 100\,\% = \underline{\underline{25\,\%}}$$

8.5.6 Checking the selected drive

Geared motor: PSF 301 EB DY 71 MLB

Rated data:
$i = 4$
$M_{amax} = 80$ Nm
$n_N = 3000\ \text{min}^{-1}$
$M_0 = 5$ Nm
$I_0 = 3.8$ A
$J_{mot} = 0.000831\ \text{kgm}^2$

Requirements:

a) $M_{amax} > M_1$
80 Nm > 22 Nm met

b) $k_j > 10$

$$k_j = \frac{J_{ext}{}^*}{J_{mot}} = \frac{0.00179\,\text{kgm}^2}{0.000831\,\text{kgm}^2} = \underline{\underline{2.15}} \quad \text{met}$$

c) $M_{1mot} < 3 \cdot M_0$

$$\frac{M_{1mot}}{M_0} = \frac{7.38\,\text{Nm}}{5\,\text{Nm}} = \underline{\underline{1.48}} \quad \text{met}$$

d) $M_{rms} < M_{perm}$

3,43 Nm < 5 Nm met
$M_{perm} = 5$ Nm; (S1 duty) from characteristic at $n = 1091\ \text{min}^{-1}$

e) $n^* \approx 0.9\, n_N$

$$\frac{n^*}{n_N} = \frac{2903\,\text{min}^{-1}}{3000\,\text{min}^{-1}} = \underline{\underline{0.97}} \quad \text{met}$$

All requirements are met.

8.5.7 Selection and design calculation of the servo controller components

Axis module

The axis module must satisfy the following selection criteria:

a) $I_N > \frac{I_{max}}{1.5}$

This condition follows from the axis modules' ability to supply 1.5 times the rated current.

$$I_{max} = \frac{M_{1mot}}{M_0} \cdot I_0 = \frac{7.38\,Nm}{5\,Nm} \cdot 3.8\,A = 5.61\,A \qquad \rightarrow \quad I_N > \underline{\underline{3.74\,A}}$$

b) $I_N > \bar{I}$

The current mean value $\bar{I}$ is a measure of the axis modules' thermal load rating.

$$\bar{I} = \frac{I_0}{M_0} \cdot \frac{1}{t_Z} \cdot \sum \left(\left| M_{xmot} \right| \cdot t_x \right)$$

$$\bar{I} = \frac{3.8\,A}{5\,Nm} \cdot \frac{1}{2.8\,s} \cdot \left[(7.38 + 1.20 + 2.30 + 6.01) \cdot 0.19 + (2.81 + 2.14) \cdot 0.336 + (2.73 + 2.73) \cdot 0.684 \right] Nms = \underline{\underline{2.34\,A}}$$

c) Checking the combinability of axis module and motor.

Selected axis module: MAS 51A-005-503-00

Rated data: I_N = 5 A
Width = 2 TE

Requirements:

a) $I_N > \frac{I_{max}}{1.5}$

5 A > 3.74 A met

b) $I_N > \bar{I}$

5 A > 2.34 A met

c) Combination of MAS 51A-005-503-00 and Motor DFY 71 MLB (3000 min^{-1}) permissible as per combination table in the catalogue.

Power supply module

The power supply module must meet the following selection criteria:

a) $P_{DC\ link\ max} \geq P_{mot\ max}$

The maximum DC link power rating must be greater than the maximum required power of the drive.

$$P_{mot\ max} = \frac{n^* \cdot M_{1Mot}{}^* \cdot 2\pi}{60 \frac{s}{min}} = \frac{2903\,min^{-1} \cdot 7.38\,Nm \cdot 2\pi}{60 \frac{s}{min}} = \underline{\underline{2244\,W}}$$

b) $P_{BRC\,max} > P_{Bmax}$

The braking power of the module must be greater than the braking power of the drive.

$$P_{Bmax} = \left|M_{7mot}\right| \cdot n^* \cdot \frac{2\pi}{60\frac{s}{min}} \cdot \eta_L = 6.01\,Nm \cdot 2903\,min^{-1} \cdot \frac{2\pi}{60\frac{s}{min}} \cdot 0.9 = \underline{\underline{1644\,W}}$$

c) $P_{DC\,link}\,N > \overline{P}$

The DC link power rating must be greater than the mean power of the drive.

$$\overline{P} = \frac{1}{t_Z} \cdot \sum \left(\tfrac{1}{2} \cdot \frac{n^* \cdot \left|M_{xmot}\right| \cdot 2\pi}{60\frac{s}{min}} \cdot t_x \right)$$

$$\overline{P} = \frac{1}{2.8\,s} \cdot \left(\tfrac{1}{2} \cdot \frac{2903\,min^{-1} \cdot 2\pi}{60\frac{s}{min}} \cdot \left[(7.38 + 1.20 + 2.30 + 6.01) \cdot 0.19 + (2.81 + 2.13) \cdot 0.336 + (2.73 + 2.73) \cdot 2.084 \right] Nms \right) = \underline{\underline{882\,W}}$$

Braking resistor duty cycle

$$cdf_{BW}\,[\%] = \frac{2 \cdot t_a + t_c}{t_Z} \cdot 100\,\% = \frac{2 \cdot 0.19\,s + 0.336\,s}{2.8\,s} \cdot 100\,\% = \underline{\underline{25.6\,\%}}$$

Normally the selection of power supply module, braking resistor, heat sink and line choke would follow at this point. Since these components shall be selected though for a multi-axis application with the MOVIDYN® modular servo controller these components will only be selected after the design calculations for the X, Y and Z axis have been completed.

8.6 Common supply of the X, Y and Z axes

When we take a look at the v/t diagram for all three axes, we see that all three axes must accelerate at the same time. The power supply module must be able to handle this “worst case”. As is evident from the v/t diagrams, the deceleration phases do not coincide. However, in the event of an emergency stop all axes must decelerate at the same time.

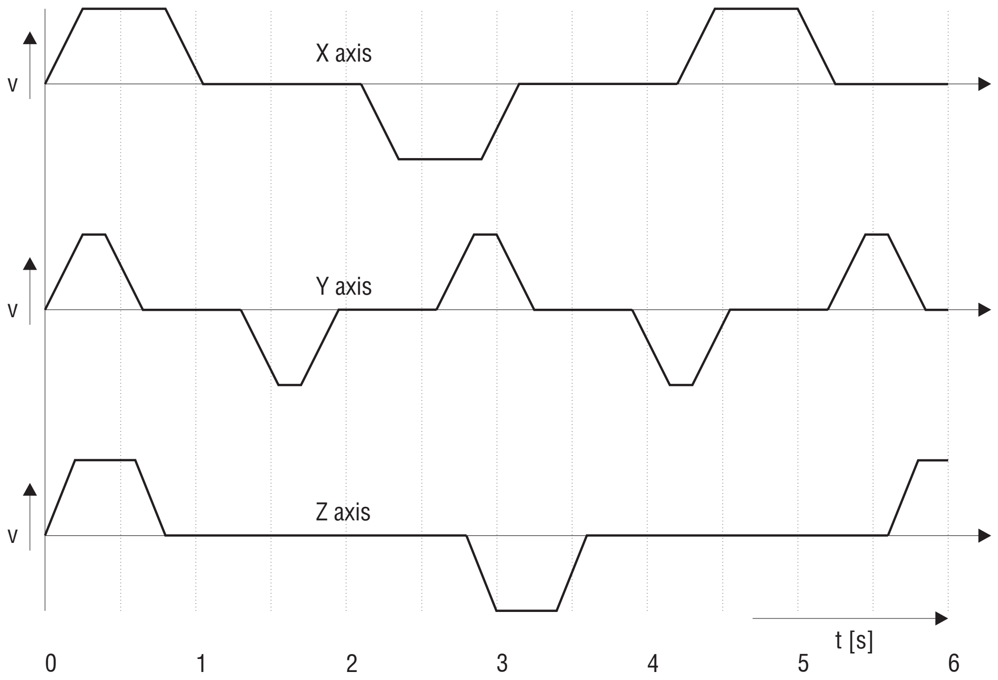

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Fig. 61: v/t diagram for all three axes

For the design calculation a demand factor of 1 is used, i.e. all axes can accelerate and decelerate at the same time. Therefore currents and torques are added up.

8.6.1 Power supply module

The power supply module must satisfy the following selection criteria:

a) $P_{\text{DC link max}} \geq P_{\text{mot max}}$

The maximum DC link power rating must be greater than the maximum required power of the drive.

$$P_{\text{mot max}} = P_{\text{mot max}_X} + P_{\text{mot max}_Y} + P_{\text{mot max}_Z} = 21306\ \text{W} + 5131\ \text{W} + 2244\ \text{W} = \underline{\underline{28681\ \text{W}}}$$

b) $P_{\text{BRC max}} > P_{\text{Bmax}}$

The braking power of the module must be greater than the braking power of the drive.

$$P_{\text{Bmax}} = P_{\text{Bmax}_X} + P_{\text{Bmax}_Y} + P_{\text{Bmax}_Z} = 11902\ \text{W} + 3150\ \text{W} + 1644\ \text{W} = \underline{\underline{16696\ \text{W}}}$$

c) $P_{\text{DC link N}} > \overline{P}$

The DC link power rating must be greater than the mean power of the drive.

$$\overline{P} = \overline{P}_X + \overline{P}_Y + \overline{P}_Z = 2643\ \text{W} + 839\ \text{W} + 882\ \text{W} = \underline{\underline{4364\ \text{W}}}$$

Selected power supply module: MPB 51A-027-503-00

Rated data:

$P_{DC\ link\ N}$ = 27 kW
$P_{DC\ link\ max}$ = 54 kW
$P_{BRC\ max}$ = 38 kW
Width = 4 TE

Requirements:

a) $P_{DC\ link\ max} \geq P_{mot\ max}$
54 kW ≥ 28.7 kW met

b) $P_{BRCmax} > P_{Bmax}$
38 kW > 16.7 kW met

c) $P_{DC\ link\ N} > \overline{P}$
27 kW > 4.4 kW met

Braking resistor

Braking resistor selection criteria:

a) $P_{N\ cdf} > \overline{P}_{regen}$

The cdf rating must be greater than the mean regenerative braking power.

$$\overline{P}_{regen} = \overline{P}_{regen_X} + \overline{P}_{regen_Y} + \overline{P}_{regen_Z} = 5951\,W + 1575\,W + 822\,W = \underline{\underline{8348\,W}}$$

The permissible cdf time is verified by approximation:

$$\text{Cyclic duration factor cdf}\,[\%] = \tfrac{1}{3}(cdf_X + cdf_Y + cdf_Z) = \tfrac{1}{3}(11.9 + 19.2 + 25.6)\% = 18.9\,\%$$

b) Checking the combinability of braking resistor and supply components

Selected braking resistor: BW 018-035

Rated data:

P_N = 3.5 kW
P_N at 25 % cdf = 10.25 kW

Requirements:

a) $P_{N\ cdf} > \overline{P}_{regen}$
10.25 kW > 8.3 kW met

b) braking resistor permissible as per catalogue met

Heat sink

The following criteria must be considered when selecting the heat sink:

a) The total width of all modules added together. Care must be taken to ensure that the modules are not mounted over the joint between two heat sinks.

b) The maximum heat sink temperature ϑ_{KKmax} (80 °C) may not be exceeded (taking account of the ambient temperature).

Required width:

MPB 51A-027-503-00:	4 TE
MAS 51A-060-503-00:	4 TE
MAS 51A-010-503-00:	2 TE
MAS 51A-005-503-00:	2 TE
Total width:	12 TE

Selected heat sinks: 1 × DKS 09 and 1 × DKS 05

The heat sinks are mounted such that one TE projects at each side.

Rated data: **DKS 09** R_{th} = 0,17 K/W
width = 9 TE

DKS 05 R_{th} = 0,27 K/W
width = 5 TE

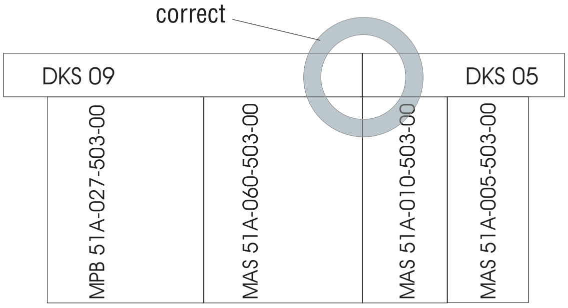

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Fig. 62: Mounting of the heat sinks

Power losses to be dissipated by the heat sink:

P_{KK} = heat sink rating
P_{VSNT} = power losses of the switch - mode power supply in the power supply module
P_{VL0} = power losses of the power supply module
$P_{VLX/Y/Z}$ = power losses of the axis modules
$\bar{I}$ = current mean value

Calculating the temperature rise when ambient temperature ϑ_{amb} = 30 °C

$$P_{KK_{09}} = \tfrac{1}{2} P_{VSNT} + P_{VL0} + P_{VLX}$$

$$P_{VSNT} = 12\,W + 3 \cdot 13\,W = 51\,W$$

$$P_{VL0} = \frac{2\,W}{A} \cdot \left(\bar{I}_1 + \bar{I}_2 + \bar{I}_3\right) = \frac{2\,W}{A} \cdot (11.5\,A + 3.92\,A + 2.34\,A) = 35.5\,W$$

$$P_{KK_{09}} = \frac{51\,W}{2} + 35.5\,W + 161\,W = \underline{\underline{222\,W}}$$

$$\Delta\vartheta_{09} = R_{th_{09}} \cdot P_{KK_{09}} = 0{,}17\,\tfrac{K}{W} \cdot 196.5\,W = \underline{\underline{33.4\,K}}$$

$$\vartheta_{KK_{09}} = \vartheta_{amb} + \Delta\vartheta_{09} = (30 + 33.4)\,°C = \underline{\underline{63.4\,°C}}$$

$$P_{KK_{05}} = P_{VLY} + P_{VLZ} = \bar{I}_Y \cdot 14\,\tfrac{W}{A} + \bar{I}_Z \cdot 14\,\tfrac{W}{A} = (3.92\,A + 2.34\,A) \cdot 14\,\tfrac{W}{A} = \underline{\underline{87.64\,W}}$$

$$\Delta\vartheta_{05} = R_{th_{05}} \cdot P_{KK_{05}} = 0.27\,\tfrac{K}{W} \cdot 87.64\,W = \underline{\underline{23.7\,K}}$$

$$\vartheta_{KK_{05}} = \vartheta_{amb} + \Delta\vartheta_{05} = (30 + 23.7)°C = \underline{\underline{53.7\,°C}}$$

Note: For an explanation of the constants used please refer to the Appendix.

Requirements:

a)	14 TE > 12 TE		met
b)	$\vartheta_{KK09} < \vartheta_{KKmax}$	63.4 °C < 80 °C	met
	$\vartheta_{KK05} < \vartheta_{KKmax}$	53.7 °C < 80 °C	met

Data bus cable and line choke

The length of the data bus cable depends on the number of axis modules connected to the power supply module:

1 MPB + 3 MAS → **DBK03**

The appropriate line choke can be found in the assignment table in the Installation and Operating Instructions.

Power supply module: MPB 51A-0503-027-00
Line choke: ND 045-013
Rated data: I_{ND} = 45 A
L_H = 0.1 mH

Overview of selected components

Geared motors:	X axis: PSF 701 EB DY 112 LB Y axis: PSF 401 EB DY 90 MB Z axis: PSF 301 EB DY 71 MLB
Axis modulel:	X axis: MAS 51A-060-503-00 Y axis: MAS 51A-010-503-00 Z axis: MAS 51A-005-503-00
Power supply modulel:	MPB 51A-027-503-00
Braking resistor:	BW 018-035
Heat sink:	DKS 09 und DKS 05
Line choke:	ND 045-013
Data bus cable:	DBK03
Software:	MD_SHELL

Determining the power losses

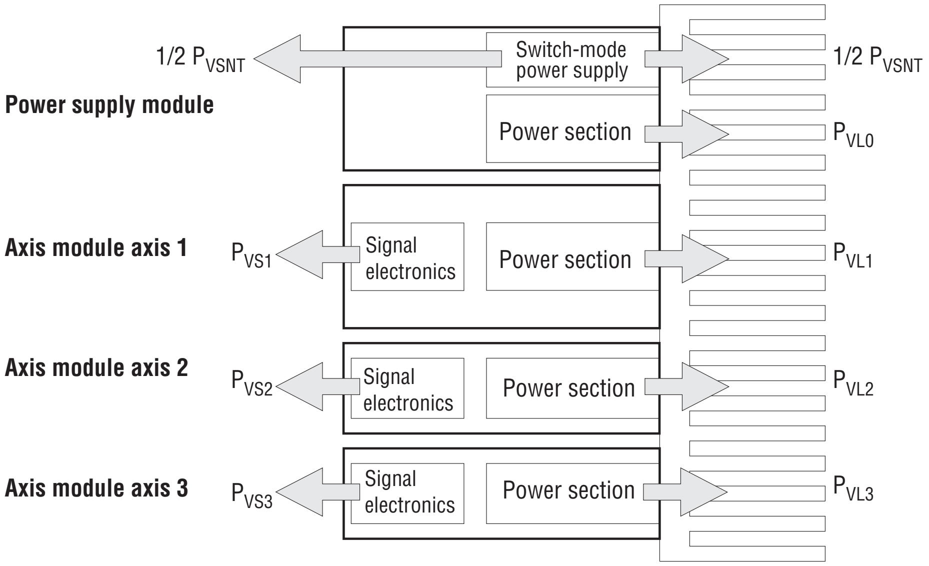

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Fig. 63: Power loss components

Power losses P_{VSNT} of the switch-mode power supply in the power supply module:

$P_{VSNT} = 12\ W + 13\ W \cdot k$
12 W = constant, power losses of the switch - mode power supply
13 W = constant, power losses for every connected axis module
k = Number of connected axis modules

Power losses P_{VL0} of the power section in the power supply module:

$P_{VL0} = \bar{I} \cdot 2\ W/A$
$\bar{I}$ = mean value of the axis module current
2 W/A = constant, power losses per amp

Power losses $P_{VL1/2/3}$ of the power section in the axis module:

$P_{VL1/2/3} = \bar{I} \cdot 14\ W/A$
$\bar{I}$ = mean value of the axis module current
14 W/A = constant, power losses per amp

Power losses P_{VS} of the signal electronics in the axis module:

$P_{VS1/2/3} = 40\ W \cdot k$
40 W = constant, power losses of the signal electronics
k = number of the joined axis modules

Total power losses to be dissipated by the heat sink:

$P_{KK} = 1/2\ P_{VSNT} + P_{VL0} + P_{VL1} + \ldots$

Power losses PSS in the switch cabinet

Heat sink mounted externally:	$P_{SS} = 1/2\ P_{VSNT} + P_{VS}$
Heat sink mounted in the switch cabinet:	$P_{SS} = 1/2\ P_{VSNT} + P_{VS} + P_{KK}$

Dimensioning of braking resistors

A servo controller with a brake chopoper requires a braking resistor to absorb the excess braking energy. The brake chopper is connected to the DC link circuit and switches on automatically if the DC link voltage $V_{DC\ link}$ reaches a certain level. The braking resistor which is connected to the brake chopper continuously absorbs energy from the DC link until the switch-off threshold of the DC link voltage is reached. During continuous braking the brake chopper switches on and off continuously (it chops).

The resistance value (Ω) of the braking resistor is determined by the maximum permissible braking current of the brake chopper transistor. The permissible resistance value for each servo controller type is given in the Technical Data.

The design rating (100% cdf rating) of the braking resistor is given by the electrical braking power which flows back into the servo controller after deduction of the losses (reverse efficiency η‘) in the machine, gearing and motor. Since the braking power is usually not continuous but for a limited period only, this aspect can also be considered in the dimensioning of the braking resistor.

In linear decelerations the braking power P_B falls linearly with the braking time tB. This means that the peak braking power at the start of the braking phase is twice as high as the mean braking power. The resulting continuous regenerative power rating of the braking resistor (100 % cdf) for a single braking operation within a cycle time (repeat cycle time) can be determined from the braking power (for 100 % cdf) with the following nomogram:

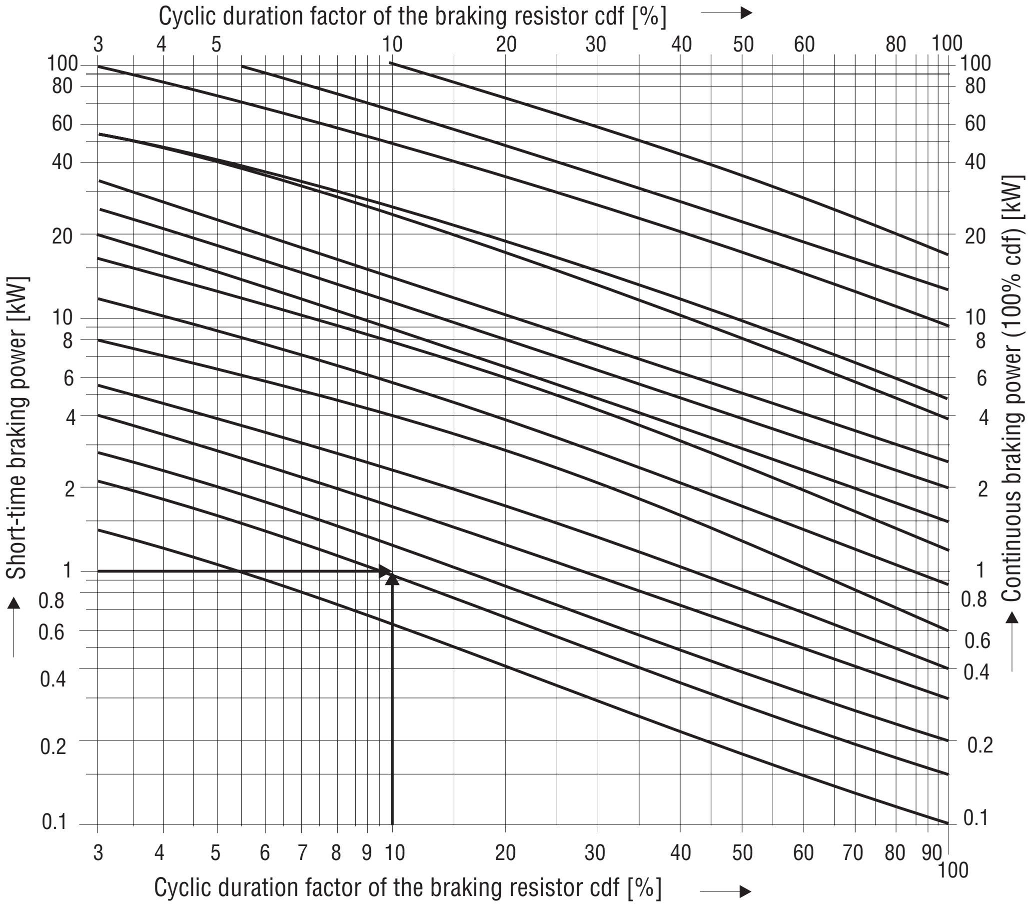

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Fig. 64: Determination of the short-time braking power for repeat cycle times (cycles ≤120 s) from the continuous resistor rating (= 100 % cdf). The lower curves (0.1 - 4 kW; see scale “continuous rating” on right) are valid for wire-wound tubular resistors, the upper curves /5/9/13/18 kW) for steel grid resistors.

Example for the selection of a braking resistor*:*
The required short-time braking power of 1 kW calls for a braking resistor with a continuous regenerative power rating of 150 W at 10 % cdf.