The Basics of Motion Control

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Prerequisites

Training modules:	no prerequisites
Software:	no prerequisites
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1. INTRODUCTION

Nearly every machine or system component today involves positioning tasks with more or less complex characteristics. The trend is clearly moving in the direction of mechatronic drive solutions.

Movement procedures that were previously implemented using mechanical constructions that were sometimes quite elaborate, can now be carried out with the highest degree of flexibility and efficiency using the latest technologies from the area of modern motion control.

Fig. 1: The basics of motion control

Uniformity of the drive solution is an important factor in this aspect. Optimum coordination of the individual components with each other brings out the true technological strengths. The mechatronic drive network is integrated into the process as a closed functional unit.

This makes it possible for development to focus mainly on optimizing the higher-level processes.

This document will describe the fundamental concepts and procedures in a clear and understandable manner.

The basic functionality of the individual components will also be covered. Special know-how is not mandatory.

1.1 Objective

Participants will learn the components of a mechatronic drive solution.

Participants will understand how different technologies function and will be familiar with their respective advantages and disadvantages.

Participants will learn the most important criteria for selecting a drive configuration.

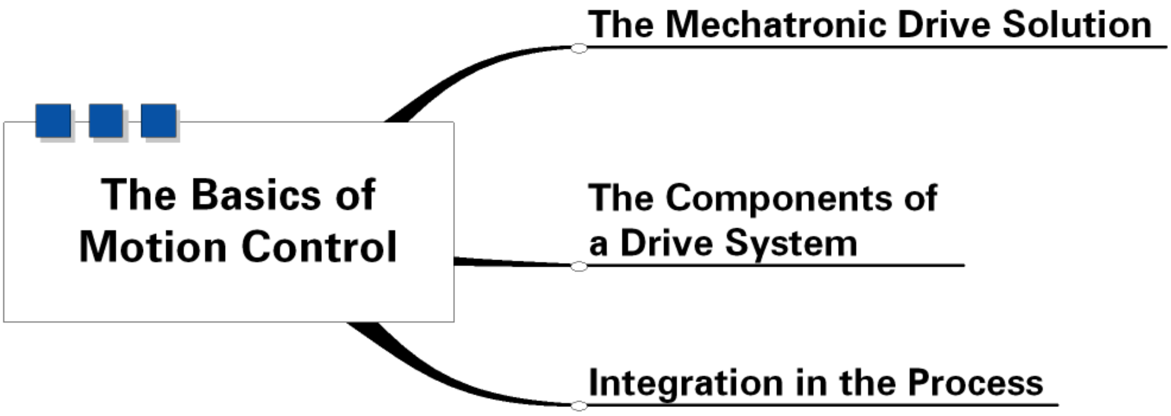


Fig. 2: Overview

2. THE MECHATRONIC DRIVE SOLUTION

...Electrical drive system, power transmission system, drive solution, drive configuration, servo drive, etc.

These (or similar) expressions are used frequently to describe the range of components in a positioning system. Defining all of this into one single term is tough to do – but why?

One thing is for certain:

There is a **wide range** of electrical drive system types. Further more, there are generally multiple designs of a single component with **specific strengths and weaknesses**.

For example, a servo-driven linear motor with high-precision position determination is required for one type of application, whereas an induction motor supplied from a frequency inverter is sufficient in another application.

Fig. 3: Orientation

Therefore, the fundamental questions are:

- **What components** actually make up a drive system or positioning system?
- What are the **differences** between the existing technologies or variations?
- **What are the separate technologies** specifically used for?

By approaching each section step-by-step, we will shed some light on these issues in no time at all.

A good place to start is with a simplified diagram, which essentially applies to all drive systems:

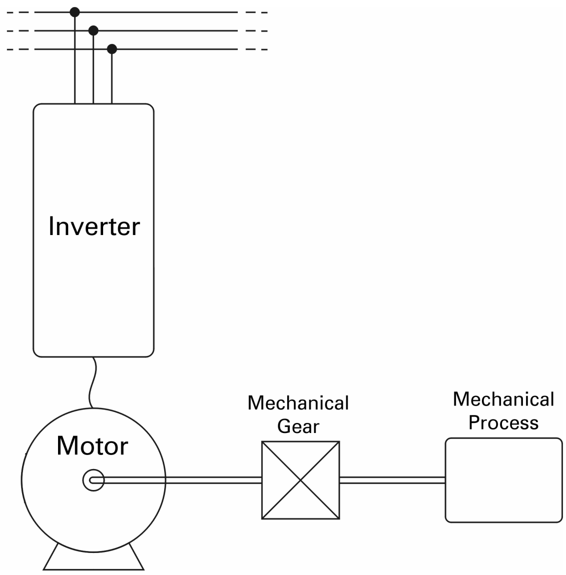


Fig. 4: Basic components

- Power converter
- Electric motor
- Mechanical gear
- Mechanical process

The power converter takes electrical energy from the mains and turns it into a suitable "form" for supplying the electric motor. The motor then converts the electrical energy into kinetic energy, thereby putting the mechanical system into motion (via a mechanical gear if necessary).

We will add to this basic scheme step-by-step as we work through the following sections. We will be concentrating on the functionality of the individual components and their properties in the complete system.

But let's first go back one step and take a quick look at a topic that involves **all aspects of modern drive technology**. We are talking about the area of **mechatronics**.

2.1 The core aspects of mechatronics

The **area of mechatronics** deals with the interaction of mechanic, electronic and information-oriented systems.

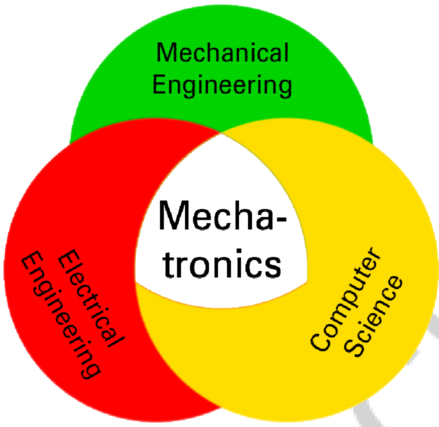


Fig. 5: Mechatronics

In mechatronics, the separation between the areas of mechanics, electricity, electronics and information technology is put aside. The system is viewed as **a single functional unit**.

The main goal is the processing of all **information** for **usage in all of these areas**.

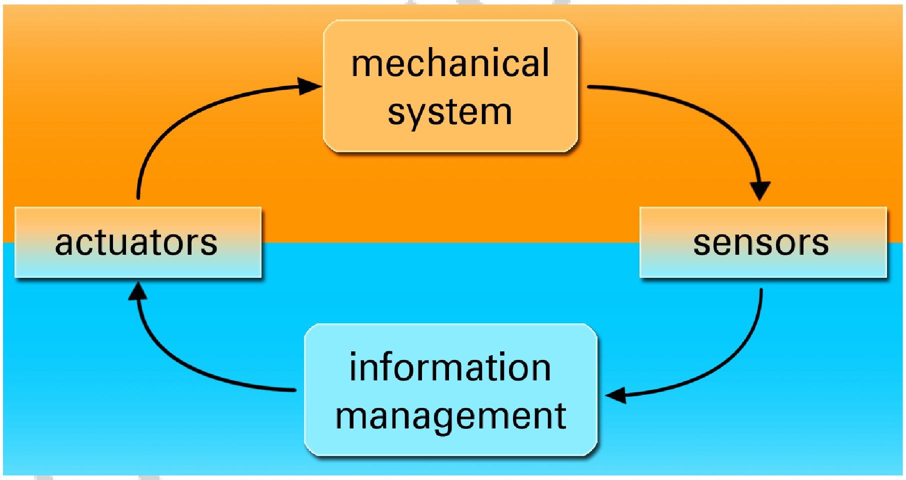


Fig. 6: Communication throughout the whole system

This is exactly the challenge when designing and setting up an electrical drive system.

In addition to the visible components such as motor or power converter (hardware), **complex control loops**, **algorithms** and a number of **communication procedures** play a decisive role in automated positioning .

Even the design and development of these technologies are carried out in close agreement with the process demands, in our case the mechanical system.

This integrated approach for mechatronics provides **clear advantages**:

- **Optimum adaptation** of the basic system to the process requirements
- Creation of **compact function units** (automation objects) and improved possibilities for standardization because the different process routines can be developed modularly and therefore easily **re-used**
- Easier **usage** thanks to standardized **user interfaces** and detailed **diagnostics possibilities**
- All of the resulting advantages for **process optimization**, efficiency, quality management (process monitoring) and many more

The advantages of the mechatronic drive solution can be seen in practical application:

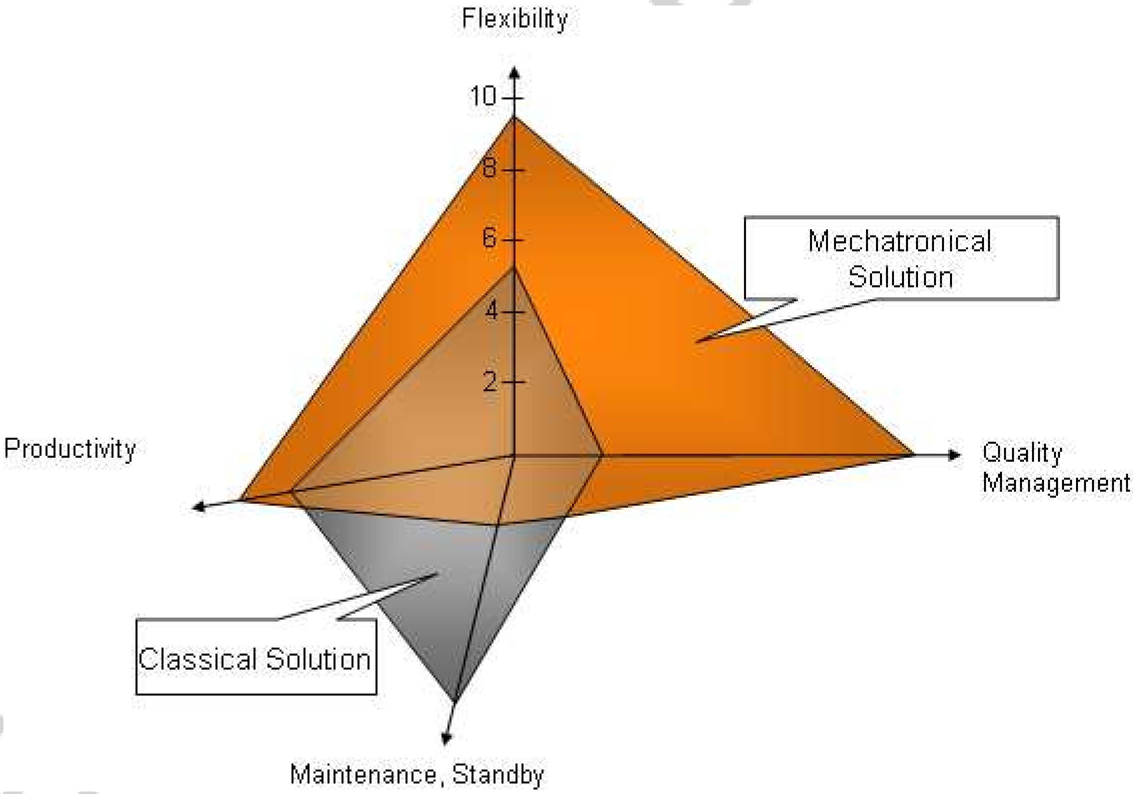


Fig. 7: Comparison

2.2 The basic requirements for a drive system

What properties characterize a drive system?

An important requirement of the system is for it to be highly **dynamic.**

The term "dynamics" (*from the Greek dynamiké – relating to power or energy*) describes general force, propulsion or force adjusted to change. This will be used to summarize development over time.

In practice, it is often necessary to achieve the following in the shortest amount of time possible:

- quickly reaching a certain speed or
- quickly reaching an exact position

Therefore, the drive system must be able to **position the connected mechanics exactly according to specification** and to **apply the highest amount of force** without "getting out of whack".

This characteristic is then applied directly to the **machine's productivity** (increased clock rate, etc.).

In many applications, **positioning precision** is also a decisive factor for the suitability of a drive system. In addition to the dynamic properties, the drive must also be able to accept exact positions and to maintain these positions with the corresponding force (e.g. with constant torque load from hanging loads).

Note:

Definition of servo drive:
Servo drives are drive systems that feature dynamic and accurate behavior able to handle overloading over a wide speed range.

Choosing the electric motor is not the only decisive factor. **Sophisticated measurement systems and control algorithms** also play a major role in accomplishing these tasks.

High demands can only be met with **compact interaction** of all components in the system.

3. THE COMPONENTS OF A DRIVE SYSTEM

The following diagram offers a somewhat detailed overview of the basic components in an electrical drive system. Although the concrete configuration can vary considerably from application to application, this general diagram is the optimum starting point for our purposes:

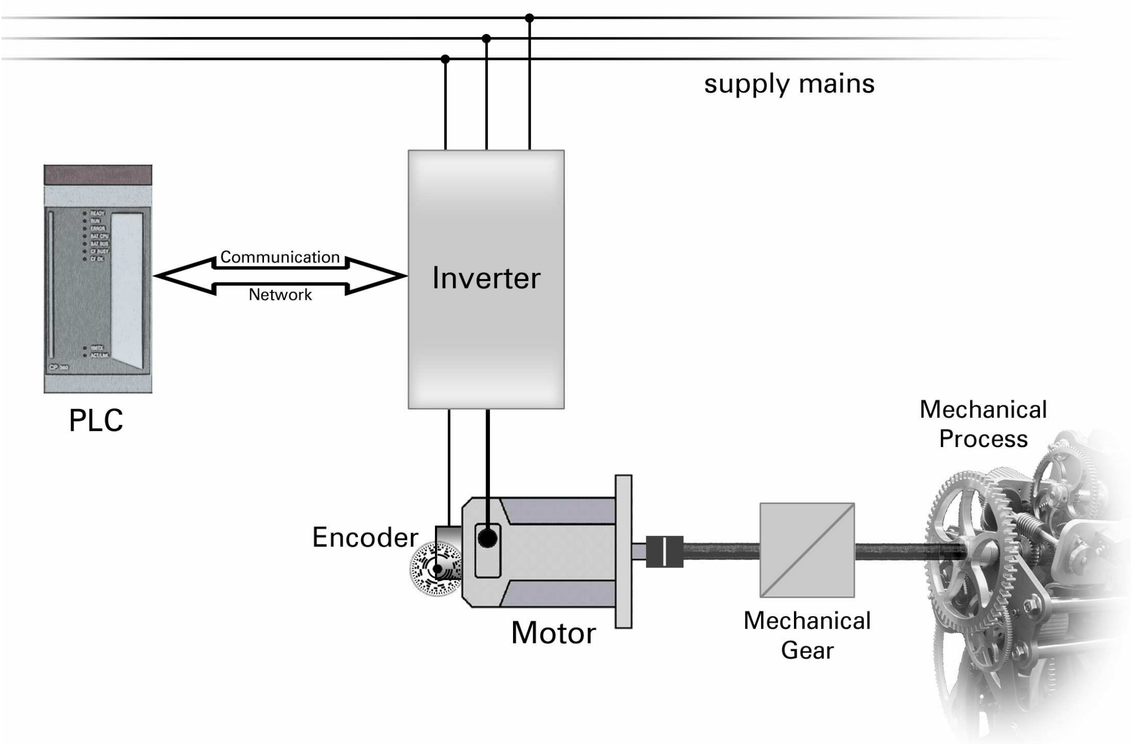


Fig. 8: The components of an electrical drive system

The working machine (mechanical process) is driven by an electric motor. When necessary, the mechanical link is made via a mechanical gear to align the speed and torque.

The **electrical drive** converts electrical energy to mechanical energy (torque, force). To control the motor movements, a **power converter** brings the electrical energy to a "useable form".

A **position encoder** provides information about the current status of the drive and the position of the machine.

The power converter then receives its commands from a control CPU. This is where the application program is executed to implement the necessary movement procedures.

Note:

Throughout the course of this document, we will get to know the two **power converter types; servo drive** and **frequency converters**. The servo drive is the considerably more "intelligent" power converter design with its ability to control highly dynamic and precisely positioned movements.

Therefore, we will spend the majority of our time with this type of power converter and will from now on be talking about "positioning systems".

3.1 Electrical drives

Since the initial development of **electromechanical energy forms** at the start of the 19th century, three different types of motors have been established which differ in structure and functionality:

- DC motors
- Synchronous motors
- Induction motors

There are many variations of these basic types e.g.: linear motors, torque motors, stepper motors, reluctance motors, etc.

We will now take a brief look at the structure of the individual motor types and become familiar with their special characteristics.

One of the three types, together with the possibilities of modern inverter technology, will prove to be specially suited for precise and dynamic positioning procedures.

3.1.1 The basic principle of electrical drives

Lorentz force is the basic physical principle for the function of electrical drives:

A **conductor with electrical current** located in a **magnetic field** is subject to a certain **force.**

This force's **direction of action** depends on the alignment of both originating values, the flow of current and the magnetic field.

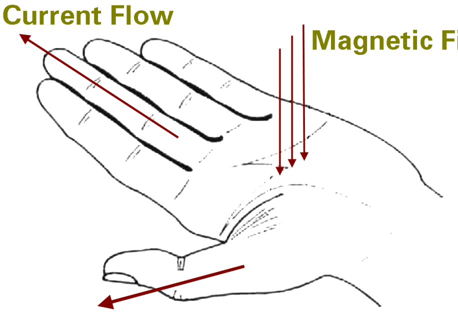


Fig. 9: "Left hand rule"

The figure above employs the "left hand rule" to illustrate the directional relationship.

The basic definition is represented mathematically as follows:

$$\vec{F} = (\vec{l} \times \vec{B}) \cdot I$$

(vector syntax)

F..... Force vector
B..... Induction vector (field lines)
l...... Length vector for the conductor in the field
I..... Current

The following formula generally represents the amount of resulting force:

$$F = I \cdot l \cdot B \cdot \sin \alpha$$

Whereby α is the angle between the direction of the magnetic field and the flow of current.

Note:

For electrical drives, this angle is almost always 90°, as illustrated in the following diagrams.

The force on the conductor depends on the **intensity of the magnetic field,** the **strength of the current** and the **length of the conductor** in this magnetic field.

The following diagrams illustrate the principle of applying this force in a rotational movement:

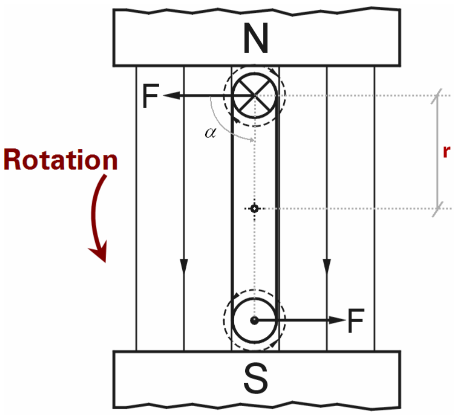


Fig. 10: Coil conducting current in the magnetic field

A pivoting coil conducting current is located in a magnetic field. A flow of current in the conductor creates mechanical force in the coil sections diagonal to the direction of the magnetic field – these sections are drawn vertical to the image plane in the diagram.

These forces affect the rotational range of the pivoting coil. The torque for the resulting rotation is represented as follows:

$$M = 2 \cdot F \cdot r \cdot \sin\alpha$$

starting from this position, the system would assume a "rest position" after a defined amount of time:

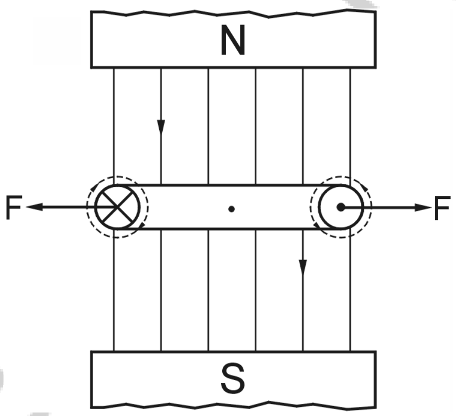


Fig. 11: Rest position

There are **two ways** now to sustain the rotational movement:

- **Reversal of the direction of current flow**

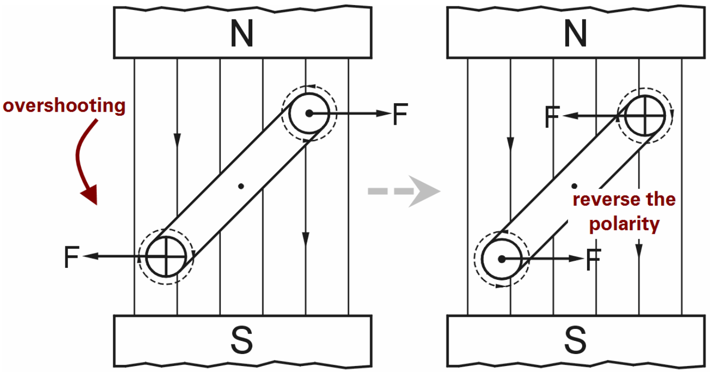


Fig. 12: Reversal of the direction of current flow

The coil rotates out of the rest position using its mechanical inertia. The flow of current is reversed at this point, thereby inverting the coil forces' direction of action. The rotational movement is continued.

- By the same token, **reversing the magnetic field polarity** would also produce the same result.

Electrical drive motors are made up of a **moving part** (the **rotor**), and a **fixed part** (the **stator**). In our example, the pivoting coil corresponds to the rotor. The magnetic field is generated by the stator.

This knowledge takes us a great step further in understanding how electrical drives function:

Commutation has the job of making sure that a conductor winding with current flowing through it is always in the exciter field in the correct position (at 0° to the field).

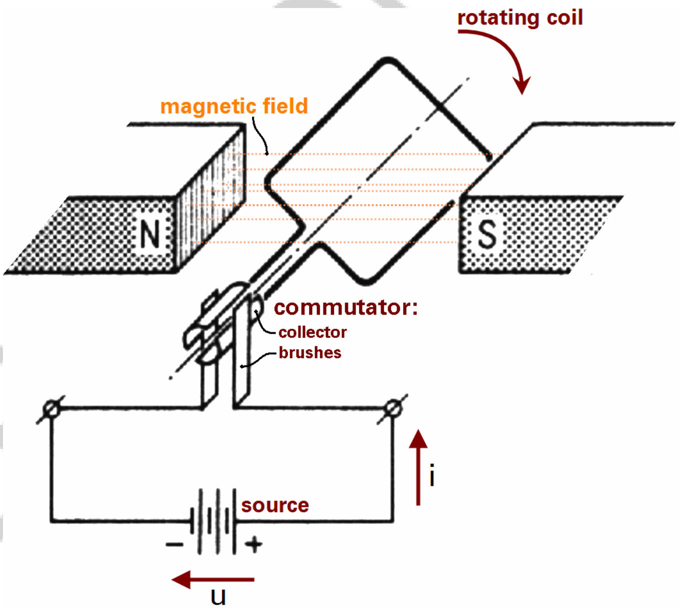


Fig. 13: Rotation caused by reversal of the direction of current

On a **DC motor** this is achieved using a **collector and brushes for establishing contact**, as shown in the above arrangement. This is also known as a **mechanical commutation.**

The **wear** of the mechanical elements in the commutator (collector, carbon brushes) and the resulting maintenance that is required represent a **disadvantage** of the collector motor.

The **change in the exciter field** (stator) can be made using electronic actuators (power transistors). The rotor is a magnet, as illustrated in the diagram below:

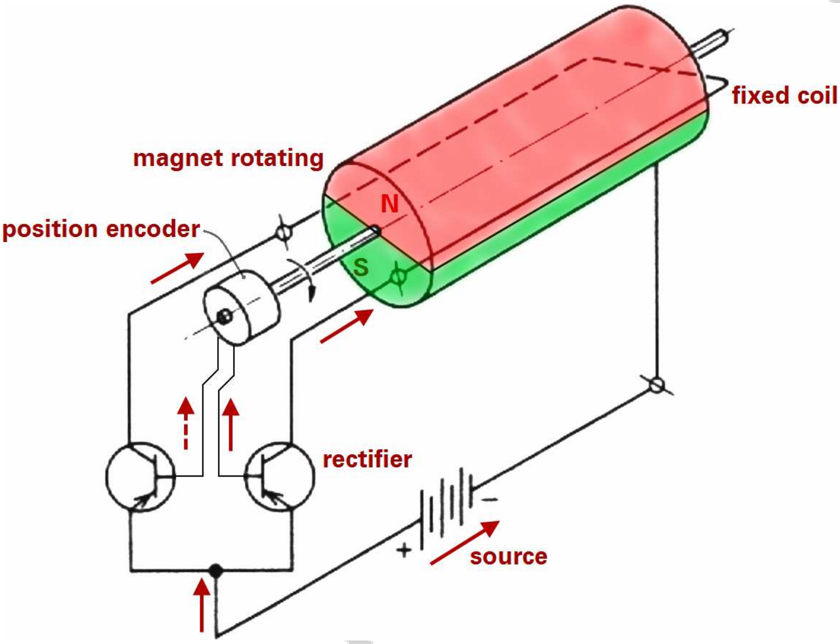


Fig. 14: Rotation caused by reversal of the magnetic field

The exciter field is inverted by **reversing the direction of the flow of current** in the exciter winding. The flow of current is controlled by electronic switching elements (power transistors), thereby eliminating mechanical parts that are subject to wear.

A **position encoder** provides the power converter with information about the **rotor's present status** for controlling the exciter field.

The rotor's present alignment must be known in order to properly control the stator windings. This is the only way for the control and switching elements to "know" how the magnetic field must to aligned.

This "electronic commutation" can be applied optimally with permanently excited synchronous motors for highly dynamic positioning movements.

3.1.2 DC motors

In the previous section we learned about the principle functionality of the DC motor.

The DM motor is designed with multiple windings on the rotor that are supplied with current via static carbon brushes on the collector when set ideally.

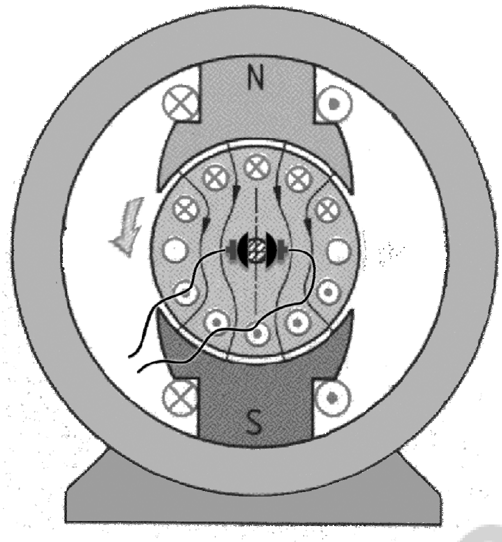


Fig. 15: DC motor structure

> **Note:**
>
> The stator field can also be divided into several poles for larger motors. The function principle always remains the same. Multiple carbon brushes ensure targeted current feed for the rotor windings.

Before the development of industrial power electronics, the **ease-of-control** of the DC motor (easy speed adjustment, etc.) made it a more beneficial motor than the three-phase motor.

The possibilities of modern drive technology for three-phase motors started pushing the DC motor more and more out of the picture for positioning applications.

However, other **areas of application** still include:

- Automotive technology
- Consumer electronics
- Actuators
- Windshield wiper motors, etc.

3.1.3 Rotating field motors (AC motors)

Developments in the area of electronics as well as materials have lead to a **shift from the DC motor to the three-phase motor** in the drive systems. Even in servo systems, which used to be used solely in DC technology, a strong tendency has been seen towards three-phase synchronous motors.

Variation of the stator field is the functional principle of the rotating field drives. The field generated by the stator coils where the rotor is located is changed with a certain timing that results in a **rotating magnetic field alignment** (-> rotating field).

The required voltage feed to the stator windings is best described using the voltage characteristics of the three-phase mains power supply (three-phase system):

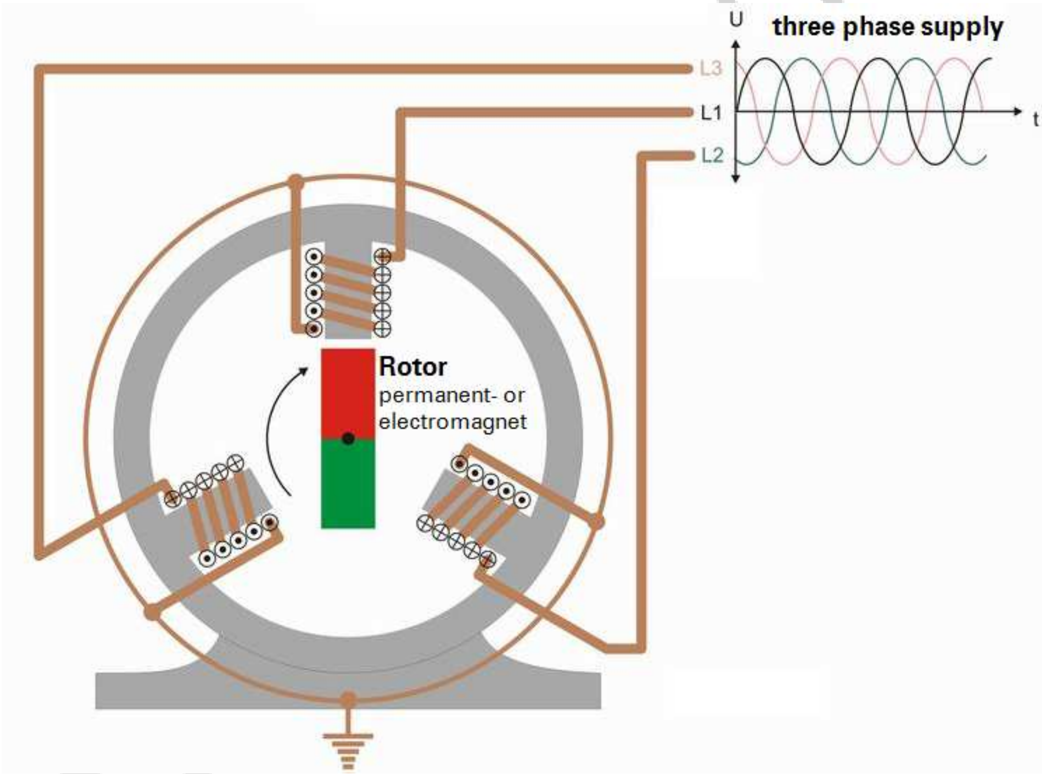


Fig. 16: Function principle of a rotating field motor

The sinusoidal supply voltage of the individual phases reach their respective peak values one after the other in periodic intervals, offset electrically by 120°. The windings are also equally distributed on the stator.

The rotor can be setup as a permanent magnet or an electromagnet (→ current-conducting coil). Therefore, we can look at the rotor as a magnet that aligns itself according to the field in which it is located.

The maximum supply voltage and therefore the **maximum of the stator field influence** moves in a circle around the stator circumference. The **magnetic field vector** made up of the individual coil fields **rotates in the stator.**

The rotor is essentially "passed" between the individual stator windings.

The manner in which the magnetic field occurs in the rotor is different in the two types of three-phase motor:

- Induction motors
- Synchronous motor

Furthermore, special designs of the rotating field motors are become more and more common. **Direct drives** are steadily gaining importance because of their special characteristics for automated positioning.

Induction motors (IM)

The stator of an IM corresponds to a rotating field motor with a three phase winding.

The rotor is different as compared to the synchronous motor because it is **not permanently excited**. Conduction bars are connected in the rotor via a short-circuit ring **(squirrel-cage motor).** This results in a system of **conductor loops**.

Voltage is induced in the conductor loops because the rotor is located in a changing magnetic field (Lenz's rule). This voltage creates a **current flow** in the conductor bars.

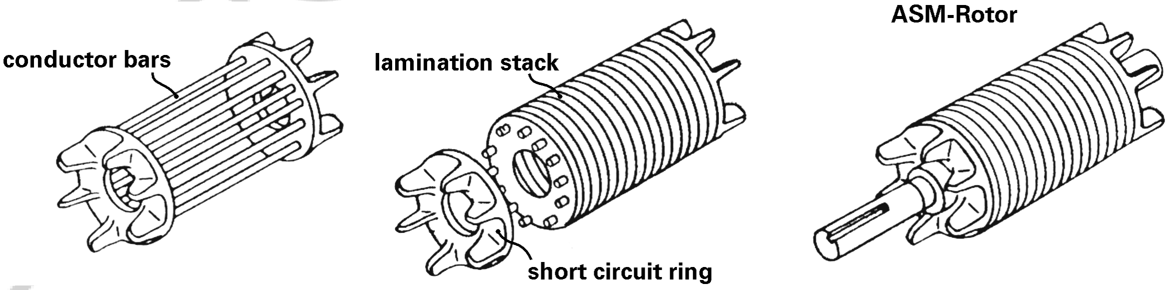


Fig. 17: IM squirrel-cage motor

A force caused by the stator field is again placed on the active conductors, which puts the rotor into motion (Lorentz force).

After starting, the rotor turns at a speed slightly under that of the rotating field. This **speed difference** ("**slip**") is necessary to induce enough current in the rotor to overcome friction, air resistance or load torque.

The rotor can never reach the speed of the rotating field, therefore the movement is **asynchronous**, resulting in the term asynchronous motor (induction motor).

Synchronous motors (SM)

The stator windings are connected to the three-phase star (U, V and W). Connecting a three-phase supply causes the **stator winding** to produce a **revolving field**.

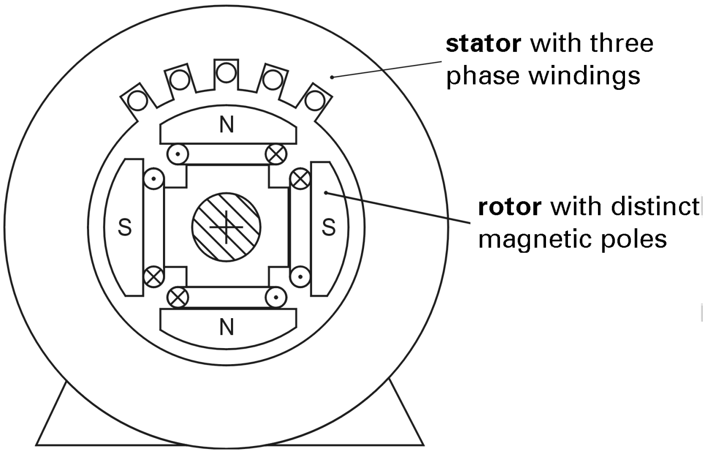


Fig. 18: Synchronous motor structure

The rotor in a synchronous motor has either an **electromagnet** (current-conducting winding arrangement) or a **permanent magnet**. The rotor field is generated "actively"

The high energy-density of new, extremely high-performance permanent magnets increases the motor's performance while simultaneously reducing the mass. This results in increased drive dynamics and smaller motor sizes. Optimized concentricity enables high-precision positioning.

Direct drive systems

Direct drives reduce the amount of mechanical transfer elements (e.g. a gear) needed between the motor and working machine.

The special motors developed for this purpose feature **high torque** (torque/sector motor) and **high thrust** (linear motor). Let's take a brief look at two common types of direct drives:

Linear motors

Translatory direct drives use the functional principles of rotating motors ("translation" = straight movement). The principle of the permanently excited synchronous motor is the most common:

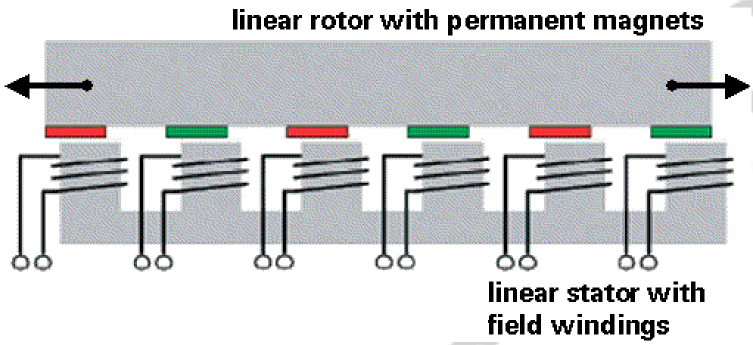


Fig. 19: Linear motor structure

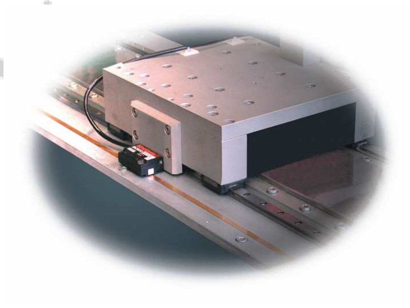


Fig. 20: Linear motor

We find the same components in linear motors as we do in the rotating field motor, **stator and rotor, but in linear arrangement.** The three-phase current feed for the stator windings positions the rotor slide linearly.

Torque motor

Regarding their construction, torque motor are generally manufactured as **multipole permanently excited synchronous motors**.

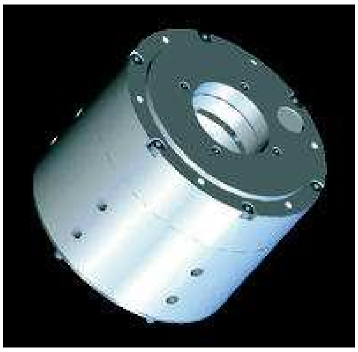


Fig. 21: Torque motor

> **Note:**
>
> **"Multipole"** means that the stator is equipped with a higher number of pole pairs. These types of motors have a lower speed and deliver a **higher torque.**
>
> $$\boxed{Torque = \frac{Power}{Speed}}$$
>
> The motor can deliver higher torque with a constant power output.

The torque motor is often built with a rotor molded into a hollow shaft. This enables the mechanical connection for **transferring high torque forces**. The torque motor can be optimized to the working machine.

The benefits in detail:

The core task is to use suitable drives to provide the forces, torque and movement forms required for carrying out processes such as conveying, mixing or separating.

The drive layout requires an **adjustment to the machine's operating point** to the load process's operating point (torque, speed). Generally, this adjustment to the process is made using a gear to accordingly converting the torque and speed:

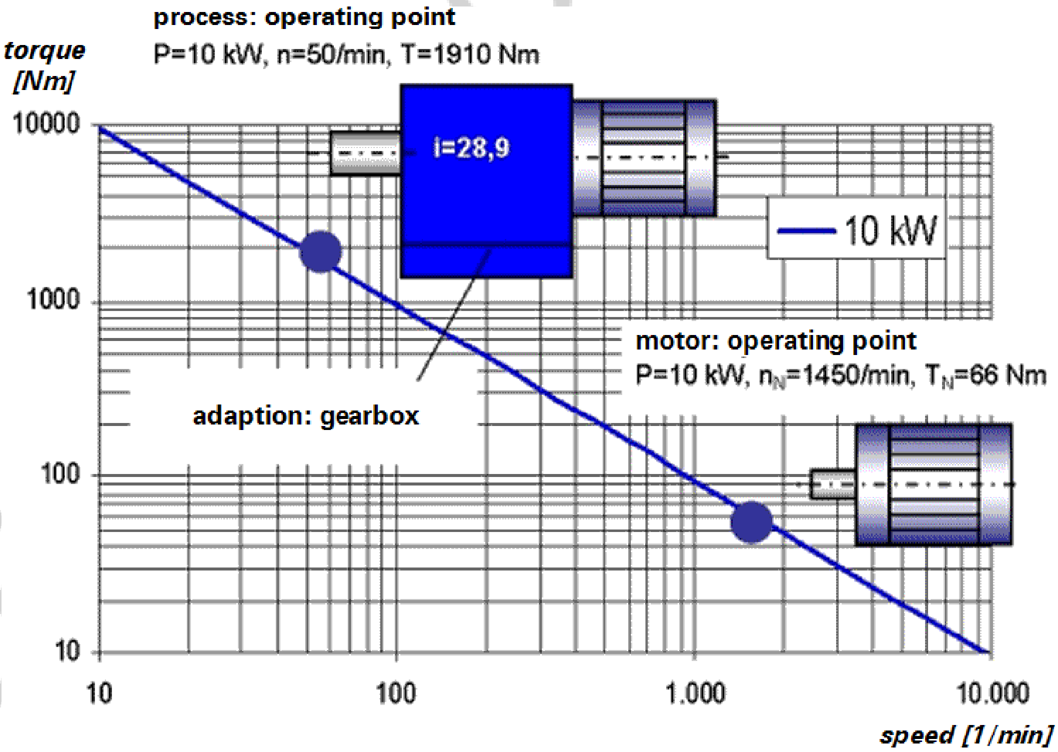


Fig. 22: Adjustment using mechanical gear

A gear is not necessary when the process operating point coincides with that of the machine. The motor – in this case the electric motor – becomes the direct drive.

A **direct drive has zero-play** because mechanical transfer elements are not used.

System values such as current, force/torque and speed/revolution can be determined directly and integrated in a control concept. In addition to improving the positioning accuracy, this also increases control of this drive.

General characteristics of the direct drive:

- Low moment of inertia
- Precision (zero-play) paired with dynamics
- Elimination of parts that are subject to wear (gear)
- Small installation dimensions
- Large hollow shaft diameter possible

The **high power density** in direct drives can cause significant heating in the drive. Therefore, they are often equipped with water or air cooling systems, which is not always necessary in comparable drives that use mechanical power conversion.

Note:

The term "**power density**" refers to a drive's peak power (in this case, the mechanical power) in relation to its mass and size.

Compared with a drive technology that has larger power density, a drive with smaller power density, designed for the same peak power, will be smaller in size and dimensions.

3.1.4 Comparison of motor types

Development over the past few years has resulted in a number of innovations and improvements in the area of microprocessors and power electronic switching elements.

Nowadays, it is possible to use **intelligent power converters** for targeted control of the stator coils allowing the **stator field** to be rotated or dynamically placed **with variable frequency** ("independent of the mains").

These conditions now make it possible to utilize the major **advantages of three-phase drives**:

- Maintenance-free operation due to the elimination of mechanical commutation
- Better cooling characteristics
- Robust design
- Synchronous motors are the best choice to meet highly dynamic movement criteria.

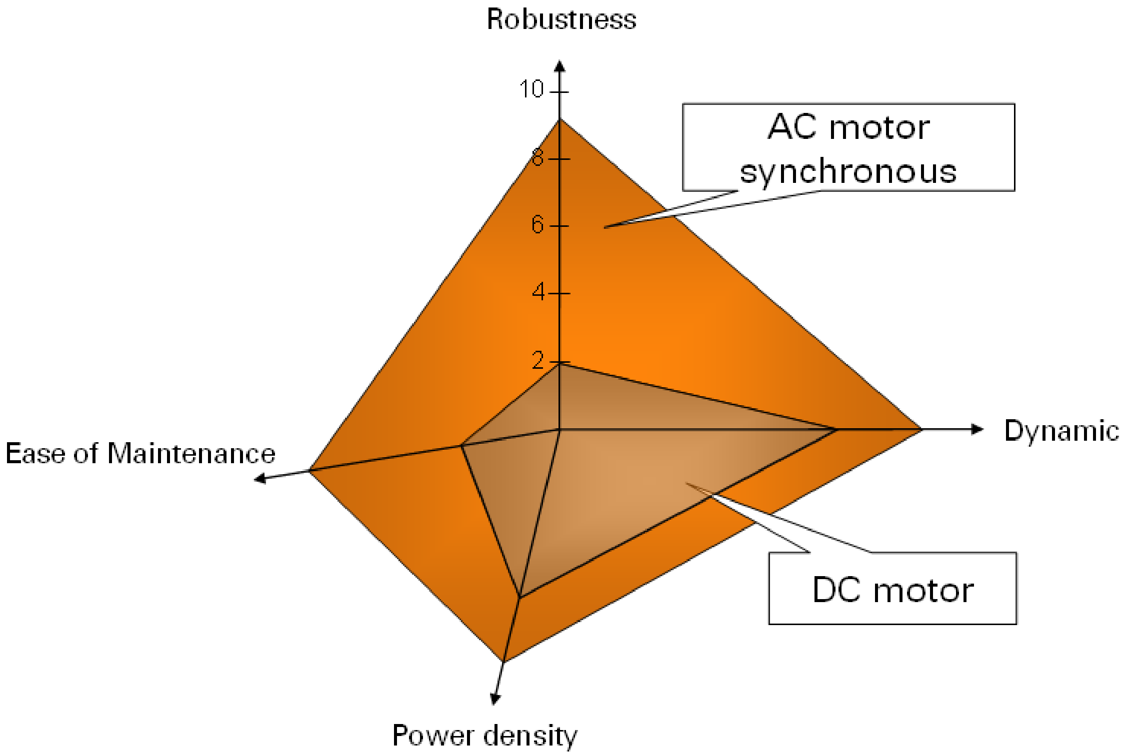


Fig. 23: Comparison of motor types

This comparison clearly shows the advantages of the **permanently excited synchronous motors** as opposed to the DC motor.

The **induction motor** is also considerably **less effective** than the permanently excited synchronous motor. In principle, the induction motor can achieve relatively high dynamic properties. However, much more complex control systems are needed than for the synchronous motor to do this. This motor type is well-suited to be **operated by a frequency inverter** (rotating field specification without reference to rotor position) and is typically used in this area.

The direct drive characteristics, usually a special design of the permanently excited synchronous motor, were already covered in the previous section.

3.2 Position encoders

The position encoder is an important part of the drive system. As the name implies, it enables **accurate determination of the position or status** of a mechanical element. The speed is then derived from this information.

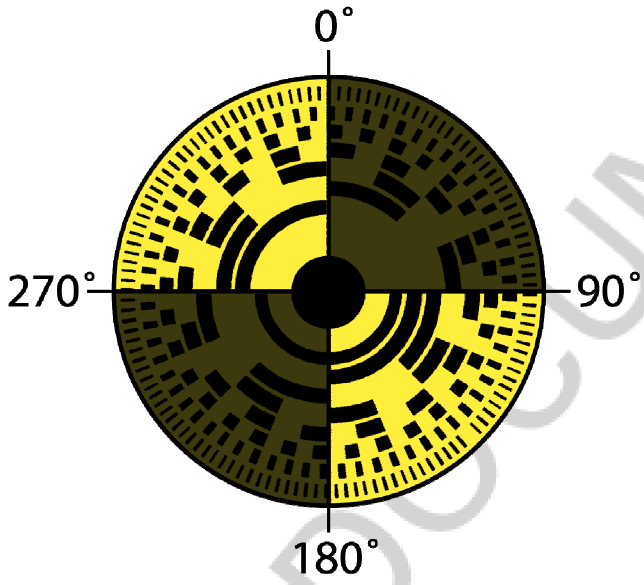


Fig. 24: Position measurement

> **Note:**
>
> In principle, a position encoder is not required for operating a frequency converter. Encoders will, in some applications, be used for position measurement, (so-called external encoders), but do not have direct contact with the frequency converter.

The position system

Clearly, the **drive position** is the fundamental information used when controlling a positioning process.

The drive system, and therefore the machine's mechanics, can only be "sent" to a **defined position** by using the following methods to introduce a unique **positioning system**:

- Defining the position of the position zero-point
- Dividing the encoder revolution into a specific number of position units

"*... move to absolute position 3000*"

"... 290 units to the right of the present position ..."

The position encoder as measuring element

The position encoder sends the actual position and speed, thereby functioning as a measurement tool in the process.

Therefore, the position encoder plays multiple roles in a **servo system**:

- The position encoder provides the servo drive with the information about the current **position and speed of the drive.** As we will see later, the stator field of the electrical drive is specifically controlled by the servo drive (electronic commutation). This control makes it possible to bring the drive rotor to a defined alignment or to dynamically put it in motion.

- As a result, the servo drive can use **internal control** to react to deviations in the drive from the predefined positioning profile (set position, set speed).

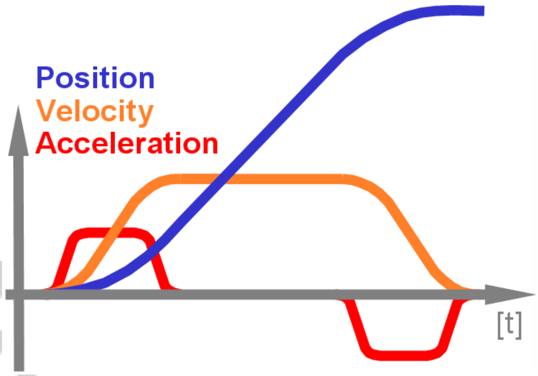


Fig. 25: Positioning profile

- A servo drive must also accurately detect the present **position of the drive rotor** (alignment of the rotor field) within a revolution to activate the control at the correct position.

That's why the position encoder is usually connected directly to the drive shaft in the motor housing of servo motors (→ motors intended for operation via a servo drive).

Resolution is an important **criteria** when selecting an encoder type**.** The resolution determines how accurately the position can be measured by the encoder within a single revolution.

This **resolution** has an additional effect on the control. It determines the degree of accuracy with which the encoder can inform the servo drive about control deviations. A high encoder resolution improves the **control quality** decisively.

Additional characteristics of encoder systems will be discussed together with the individual encoder types.

3.2.1 Optical incremental encoder

Structure and functionality

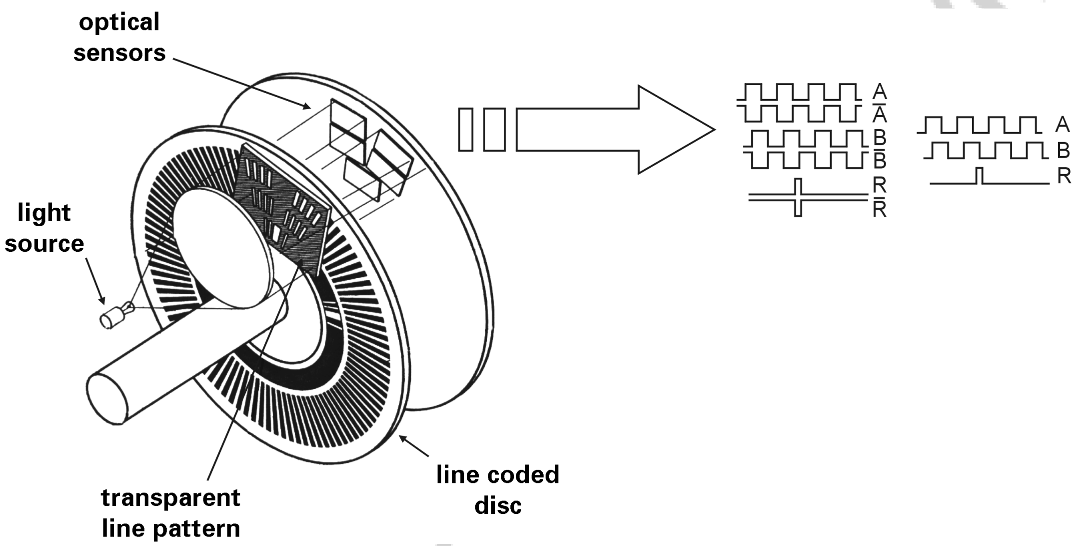


Fig. 26: Optical incremental encoder: Structure and measurement signal

Placing a **slot mask over the line code disk** creates a sine and 90° offset cosine signal that is converted to a **square wave encoder signal**.

They are used by the processing logic in the system (electronics) to increment/decrement a position counter.

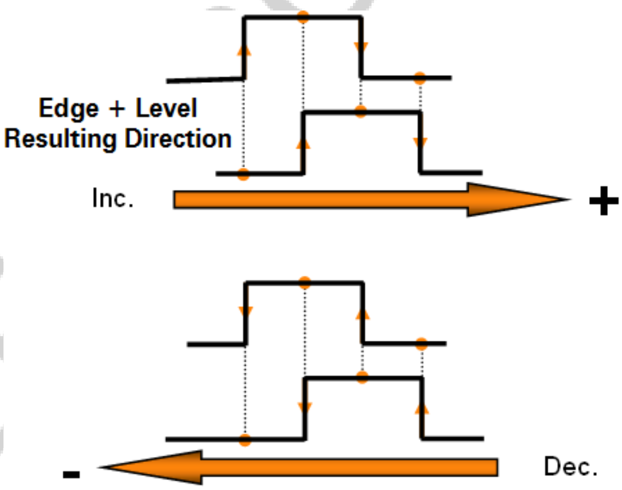


Fig. 27: Signal evaluation

When using an incremental encoder, the position of the mechanics (→ encoder position) cannot be concluded right away due to the encoder information. Only the "increment" is recognized in positive or negative direction as position information.

The incremental encoder **cannot determine the position of the encoder within one revolution**.

An additional **reference track** provides an "improvised" indication for determining the position within one revolution. In order to create a relationship between the counter and the current position, a **homing procedure** has to be carried out.

Note:

A **homing procedure** must be performed to prepare the position system (initialize) before a positioning procedure.

To do this, the mechanical system is generally brought to a defined position, e.g. by approaching a fixed reference switch:

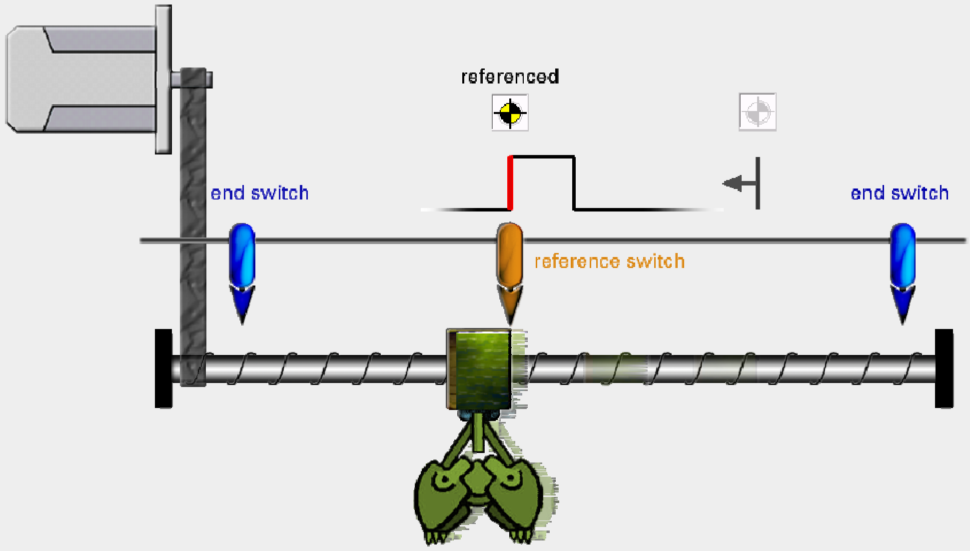


Fig. 28: Homing procedure

The present position is then assigned a defined value (for the software-based positioning). From this point on, the drive system effectively knows where the mechanics are located. Positioning can now be started.

The resolution of the incremental encoder depends on the number of lines, the type of evaluation (1x, 2x, 4x) and the maximum input frequency of the processing logic.

The optical incremental encoder has a very **high resolution** (several million increments possible per revolution) and features **high-speed evaluation**.

This is clearly an advantage for controlling the servo drive (speed, position etc.). Information about deviation of the present values from the set values is very quickly available on the servo drive. Reaction is possible within minimal dwell time.

3.2.2 Resolver – inductive absolute value encoder

The military designed a very robust encoder with simple construction – the resolver.

Structure and functionality

The resolver works on the **principle of a rotary transformer.** In a rotary transformer, the rotor consists of a coil (winding), which together with the stator winding, makes up a transformer.

The resolver is essentially built the same way, with the difference that the stator is made up of **two winders offset from each other by 90°** instead of just one:

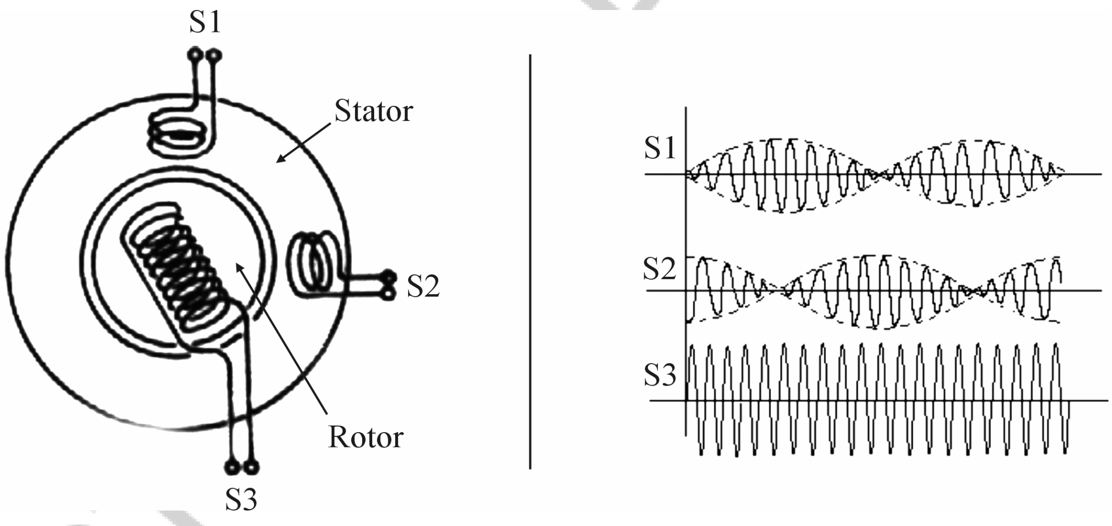


Fig. 29: Resolver: Structure and measurement signal

The signal is generated by feeding a sine signal with constant frequency in the rotor coil (S3). This uses the transformer principle to transfer voltages S1 and S2 to the 90° offset stator coils.

The signal curve for S1 and S2 (shown above) results when the rotor starts to move. The **envelope curves** for these signals depict two sine curves offset by 90°. The processing logic uses this information to determine the position.

If the movement area for the axis is **within one encoder revolution**, each encoder value corresponds to a **unique position** (homing is not necessary).

The output signal is repeated on the resolver (the position information from the envelope curves) with each new revolution. If for example, you deactivated the drive system and manually turned the motor shaft 360°, the system would have no chance of detecting this manipulation.

If the movement range of the machine exceeds this one revolution, then a **homing procedure** must be performed on the resolver (in most cases) after **restarting the system**.

The **resolution** of the resolver depends on the processing logic and the frequency of the supply for the rotor coil (4096/16384 increments).

A specific amount of time passes before the **processing logic** sends the corresponding value about the present position. This means an additional **dead time** for the control loop. This dead time affects the control quality.

3.2.3 Optical absolute value encoder

Structure and functionality

Absolute encoders have a unique value for every encoder position. The resolution of an encoder revolution is realized using a **bit-coded optical encoder disk**:

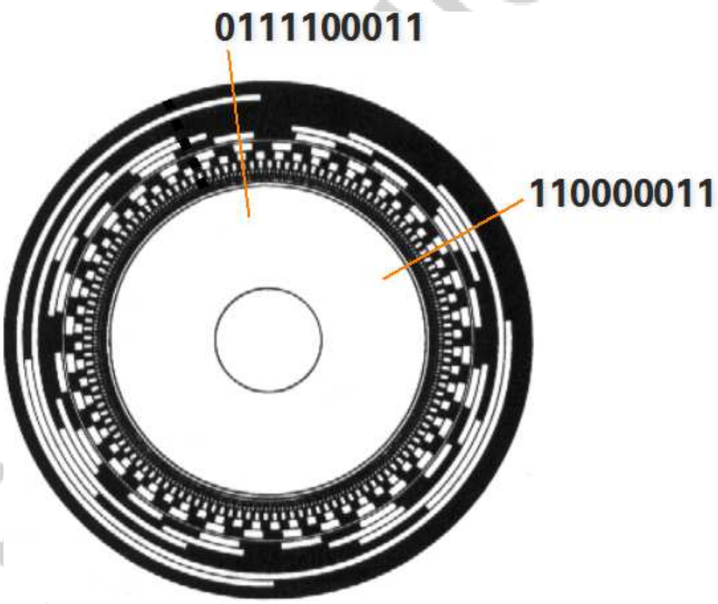
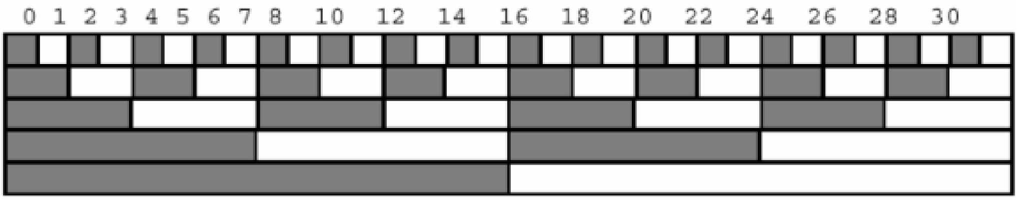
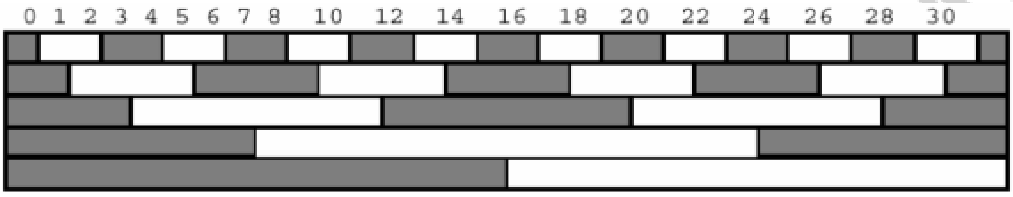


Fig. 30: Optical absolute encoder: Binary-coded encoder disk

The disks can be binary or gray code.



Binary Coded



Gray Coded

The position is given as a bit combination - each bit is a spur on the encoder disk.

Signal transfer to the processing logic takes place using the SSI protocol (Synchronous Serial Interface).

- **Synchronous**: Position data is sent to a clock signal
- Serial: Position data is sent consecutively at a certain baud rate.

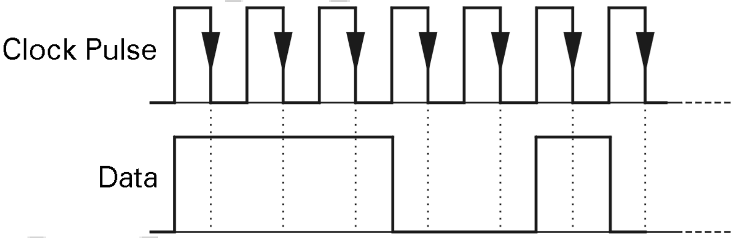


Fig. 31: SSI data transfer diagram

The current position value is accepted with a falling edge on the clock signal. The data bits of this value are then transferred to the servo drive in time with the subsequent positive edges. The transfer is linked with a defined dwell time.

As we can see, a full encoder revolution can be explicitly triggered with the optical absolute value encoder, similar to the resolver. In this case, we are talking about **single-turn encoders**.

A homing procedure is not necessary for this encoder as long as the **range of one motor revolution** is not exceeded during positioning. The encoder displays an explicit value after starting the system (power-up). This value can then be used to figure out the position of the mechanics.

The **multi-turn encoder** is the expanded version of the single-turn encoder. The explicit resolution of an encoder revolution (single-turn) is expanded with a **counting mechanism**, which determines the **number of complete revolutions**.

This information is used to stretch the explicitly defined position measurement range to a specific number of revolutions (typically 4096 revolutions).

A homing procedure is no longer necessary when using a multi-turn encoder. The current machine position can be figured out immediately once the **position offset** has been determined one time.

Note:

The **position offset** is the difference between the actual internal encoder position and the machine position.

For example: The mechanics are in the zero position, the software-based position should be set to zero there (position = 0), present encoder position value = 56343, (i.e. offset= 56343):

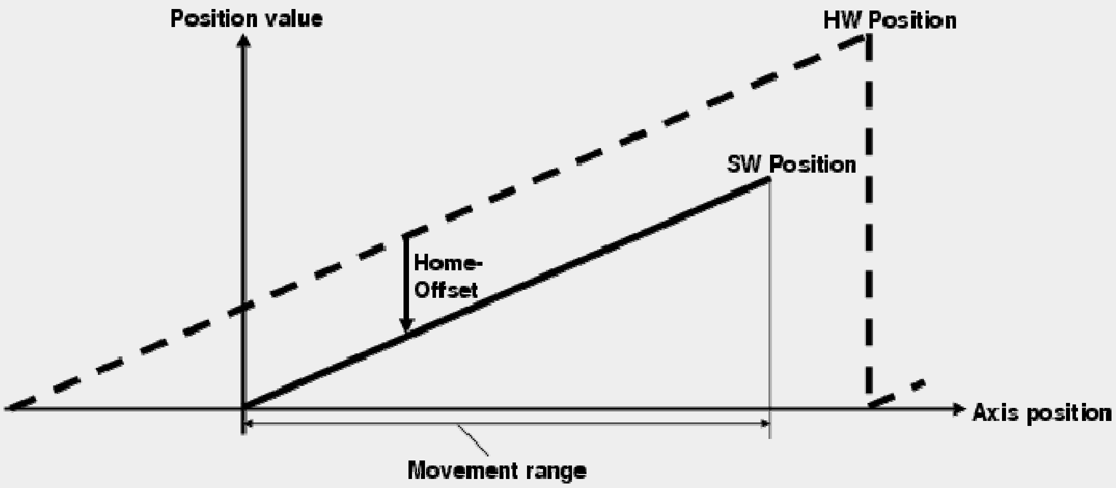


Fig. 32: Encoder offset

This offset can be used from any position to figure out the position of the mechanics.

This counting mechanism is implemented either with an additional mechanical transfer gear or an electronic logic.

3.2.4 ENDAT – Optical sine encoder

Structure and functionality

ENDAT position encoders (**EN**coder**DAT**a) combine the two types of optical encoders, **incremental encoder and absolute value encoder**. This makes it possible to utilize the advantages of both technologies:

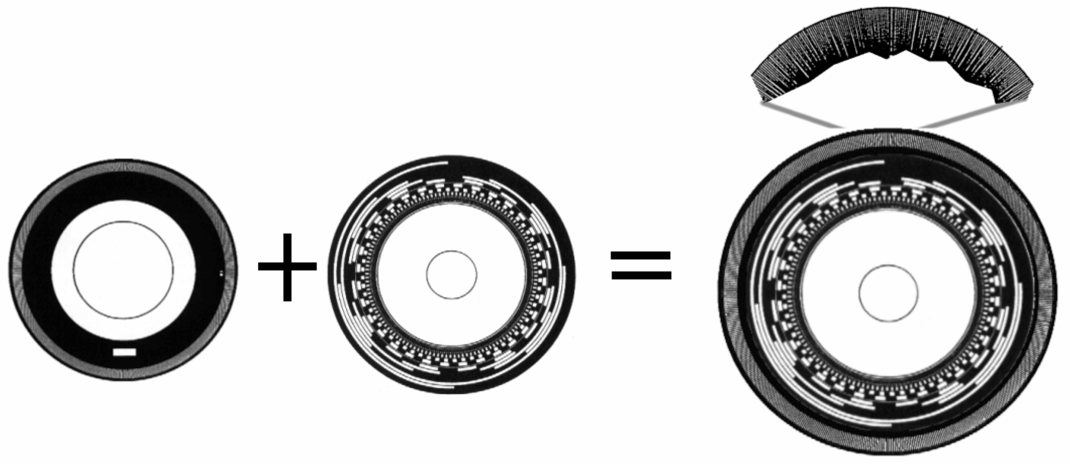


Fig. 33: ENDAT structure

- Incremental encoders
  The advantages of this encoder type are **high-speed signal transfer** and extremely **high resolution** because of sine evaluation. These characteristics create the ideal conditions for drive control.

- Absolute encoders
  There is a **constant link** (offset) between encoder and machine position. The encoder position can be used to figure out the current position of the mechanics (-> "software position" for the control program). A **homing procedure is not necessary**.

  Of course the valid movement range for the encoder must be taken into consideration (single-turn / multi-turn).

Embedded parameter chip (EDS – "electronic datasheet")

The ENDAT encoder system has nonvolatile, maintenance-free EEPROM data memory onboard. **All data required to operate the drive is stored here**.

Variables such as motor parameters and characteristics of the encoder are pre-programmed on this memory by B&R. The data is automatically transferred to the servo drive via the SSI connection when the system is started (power-up).

3.2.5 Comparison of encoder systems

With high resolution and fast signal evaluation, the **ENDAT system** provides the optimum conditions for drive control. This guarantees the **best concentricity** and **highest rigidity** for optimally timed and precise movements.

The **possibility of explicit position determination** (absolute encoder) throughout the entire movement range (multi-turn) optimizes the control process. Positioning can be started "immediately" without a homing procedure.

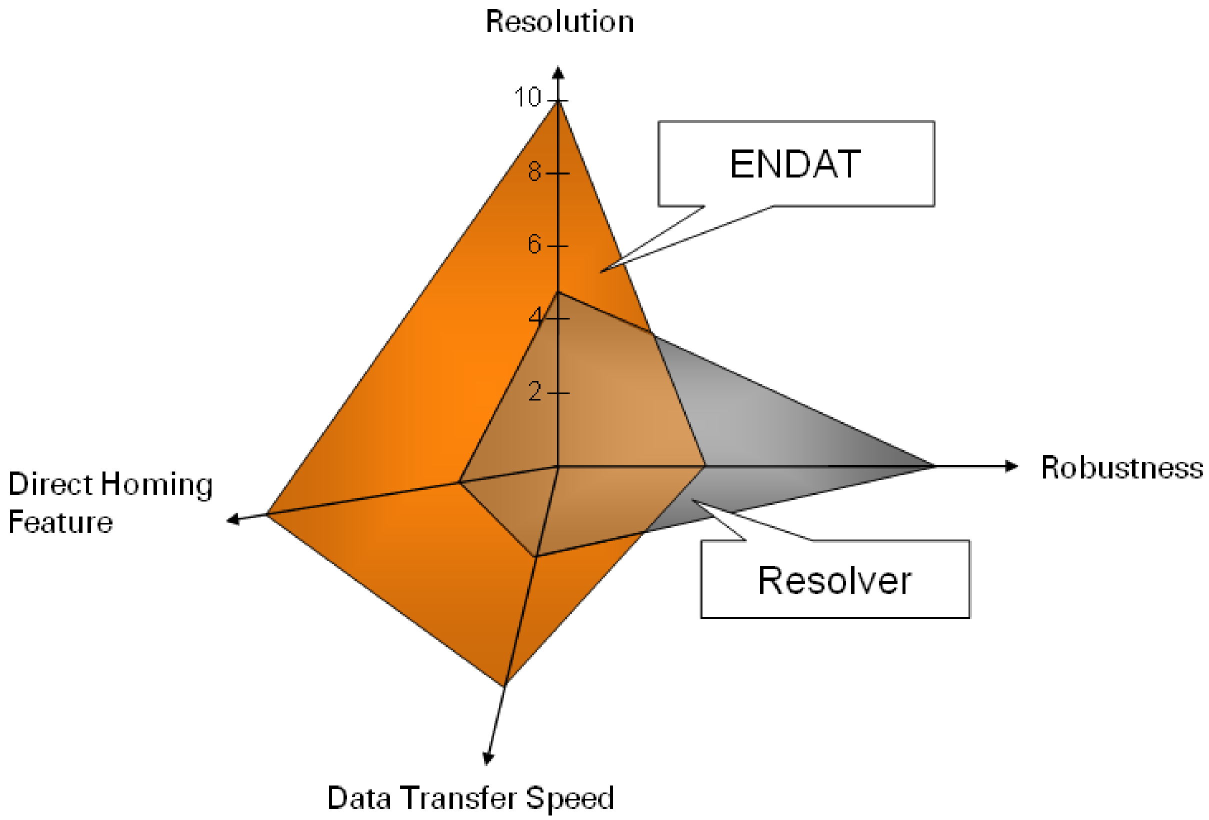


Fig. 34: Comparison of encoder systems

Compared to the ENDAT system, the resolver has the advantage of a highly robust construction. Resistance to high temperatures and mechanical vibrations makes it suitable for usage in harsher environments.

3.3 Power converter

General definition

A power converter's job is to **convert electrical energy** from a mains power supply for the operation of electrical drives.

Why is this conversion necessary?

As we now know, the **stator field** for rotating field motors can be "set" using the voltage **supply of the stator windings**. The alignment and intensity of the magnetic field in the stator result from the respective winding voltages.

The **power mains** provides a single or multi-phase AC voltage (e.g. a 3-phase supply with 50 Hz).

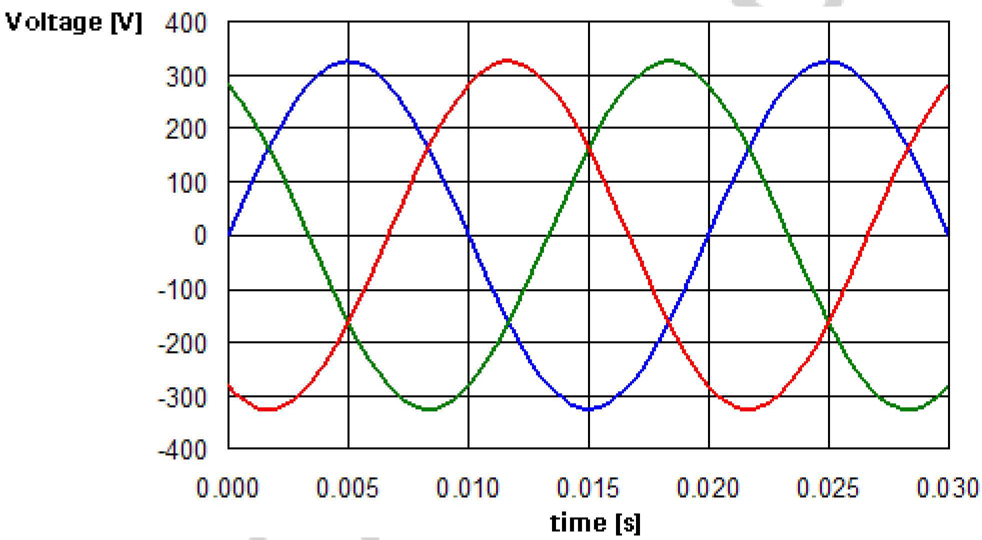


Fig. 35: Power mains

As you can see in the figure above, **sinusoidal voltages** are provided **with a constant frequency and amplitude** (so-called three-phase current).

An AC motor (IM, in some cases also the SM) can be operated directly on this power mains. As a result, the motor's stator field rotates at the frequency of the supply voltages.

Note:

The actual speed of the rotor in an induction motor is set just below the synchronous frequency. The synchronous motor would move exactly with the rotating field.

A power converter is now needed to specifically control the characteristic of the stator voltages for positioning. The converter takes electrical energy from the mains supply and passes on the voltage characteristics required for positioning to the motor.

In the following section, we will break the power converter down into general, easily-understandable parts.

There are **considerable differences** between the two main types of power converters in electrical drive technology, which will be looked at in detail at the end:

- **Frequency converter** and
- **Servo drives**

3.3.1 Function principle

The principle behind the **power electronics** is generally the same for frequency converters and servo drives. It consists of three parts:

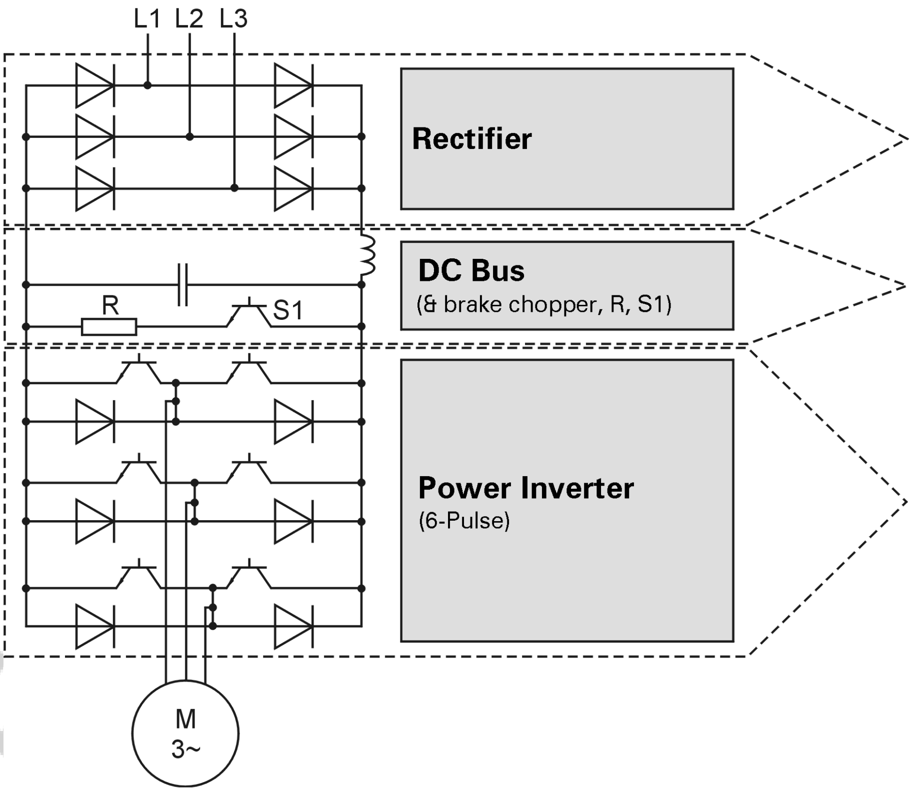


Fig. 36: Power conversion principle - power electronics

- **Rectifier**, in this case - bridge rectifier
- **DC bus**, in this case - voltage DC bus
- **Power inverter**, in this case - 6 pulse inverter

The **bridge rectifier** generates a **DC voltage** from the sinusoidal AC voltage of the power mains**.**

This DC voltage is **stored** in the so-called **DC bus.** The DC bus capacitor takes over storage of the electrical energy. In this manner, the DC bus becomes a sort of **"energy pool"** from which the downstream power inverter can draw energy.

The **voltage required to control the motor is clocked** from the DC bus voltage.

Let's take a quick look at an **important component** of the power inverter – the **IGBT** (Insulated-Gate-Bipolar-Transistor):

The IGBT, as electronic switching element, combines the advantages of MOSFET technology and bipolar transistor technology:

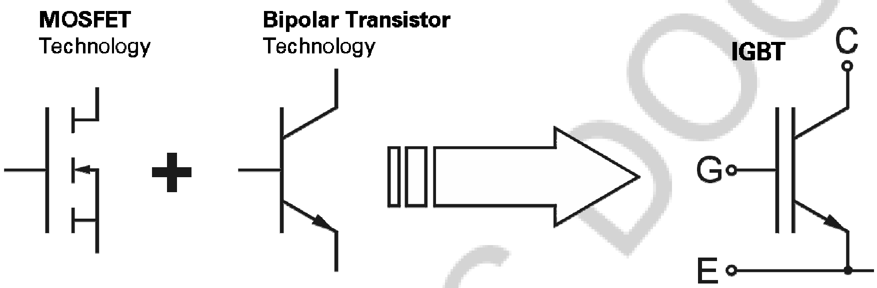


Fig. 37: IGBT structure

It features ease-of-control, good passband response and high dielectric strength. The IGBTs in the power inverter are controlled by the **signal electronics** of the power converter.

Pulse width modulation (PWM) offers a highly-flexible method for generating a **dynamic voltage characteristic**.

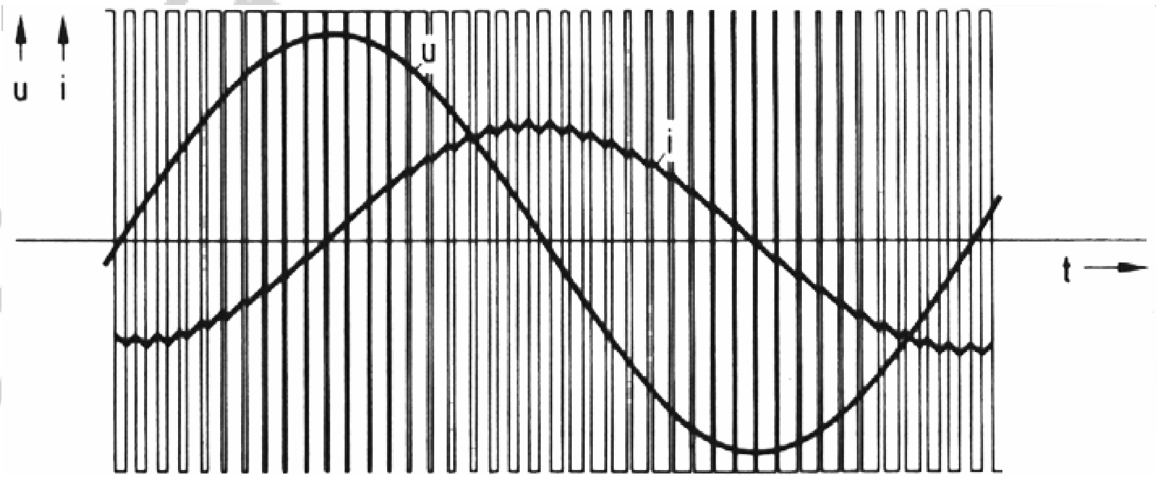


Fig. 38: Pulse width modulation

Note:

Closing or opening the voltage valve within a constant period with the **pulse width modulation** generates a specific effective value on the output. The longer the valve is open within a cycle, the larger the effective output value of this period.

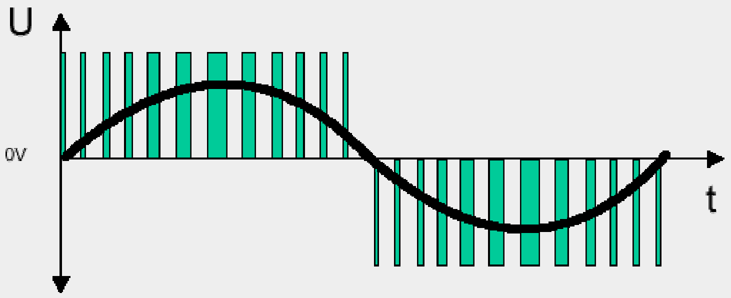


Fig. 39: Pulse width modulation principle

The clock frequency is a decisive factor for the quality of the effective value generation.

3.3.2 Other components

We will now add a **few more important function units of the power converter**.

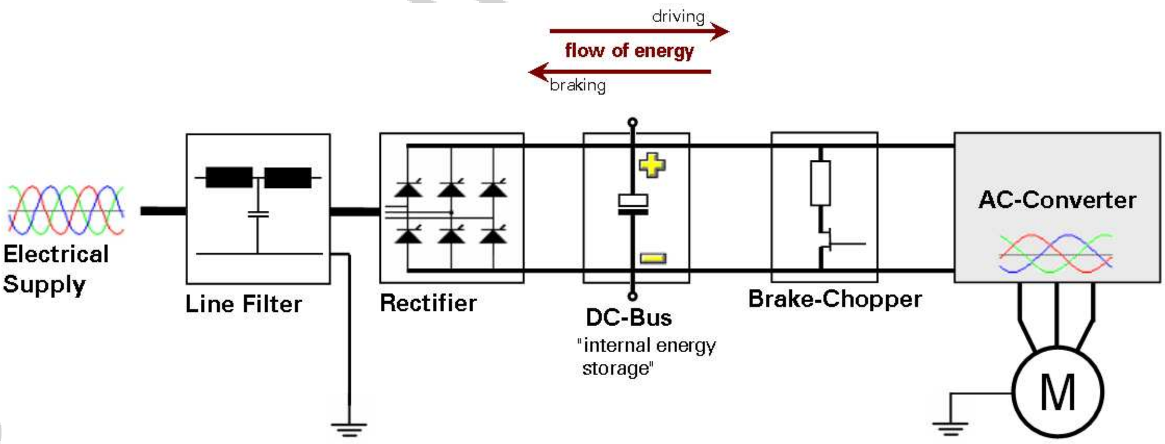


Fig. 40: Power converter structure

Line filters

In some operating conditions, the power converter can cause **disturbance signals in the mains power supply** (rectifier and power inverter). A line filter is integrated to avoid **interfering with the mains supply** and influencing other components on the supply network.

Energy returned to the DC bus

When **motor braking** is active, this is operated by the power converter as **generator**. The kinetic energy of the mechanical system is reconverted to electrical energy. This is then absorbed by the DC bus. From there, this **"energy surplus"** can be used in the following ways:

- Method: **Linking the DC bus**

  The DC bus voltage can be contacted on the power converter module via a connector. This makes it possible for modules to be electrically linked together in a parallel structure – essentially resulting in a common energy pool for the linked drive modules.

  A drive that has "extra" energy from a braking procedure makes this energy available to the other components in the DC bus network. In this case, the energy in the system is also used optimally.

- Method: **Braking resistor / brake chopper**

  Here, the excessive energy that cannot be absorbed by the DC bus is converted to heat via a power resistor (braking resistor).

  The brake-chopper (electrical valve) clocks the DC bus voltage on the resistance. When the maximum braking energy is reached, the power switch is opened completely.

- Method: **Power regeneration unit**

  The excessive energy in the DC bus can be regenerated into the mains power supply. An additional power inverter with opposite processing direction takes over the respective regeneration of voltage to the mains power supply. This results in optimized energy consumption.

Temperature monitoring

The **present thermal relationships in the system** are important for operating the power converter. Certain elements become warm during operation, but cannot exceed critical temperatures.

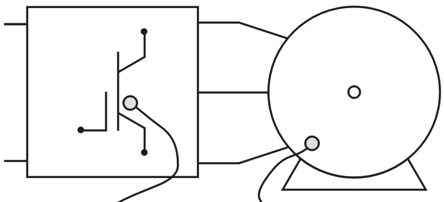


Fig. 41: Power converter, temperature monitoring

IGBT - junction temperature

The junction temperature of these power transistors must be monitored. A sensor is used to measure the temperature on the IGBT heat sink because a **measurement cannot be made directly in the component**. The structure of the IGBTs is known exactly (thermal transitions). With this measurement value, a **temperature model** can be used to determine the actual junction temperature.

Motor windings

The stator windings are heated up when a load is placed on the motor. Sensors are also used in this case to determine the **current value**. **Additionally**, a temperature model is also used to **calculate the winding temperature** from the present stator currents**.** This is how the system compensates for the delayed heating of the sensor ("thermal inertia"). This provides **optimum protection** for the **motor.**

3.3.3 Signal electronics, control and software

Who actually manages the power electronic components and the evaluation of the monitor signals in the power converter?

The control loops of a power converter can be efficiently implemented on **highly-integrated processors** (use of the **F**loating-**P**oint-**U**nit for high-end devices). The extremely high processing speed of modern technologies allows optimum clock rates for power control (typically 5 to 20 kHz).

The processor with its supporting electronic elements (memory units, etc.) makes up the foundation for the "**drive management system**" on the power converter.

> **Note:**
>
> The term "drive management system" is used here to represent the entire range of electronic and software components responsible for the IT tasks on the power converter.

Compact and powerful **algorithms** use this basis to solve the control-related tasks. The **monitoring mechanisms** and **services for operating** the drive (application interface) are also managed by this system:

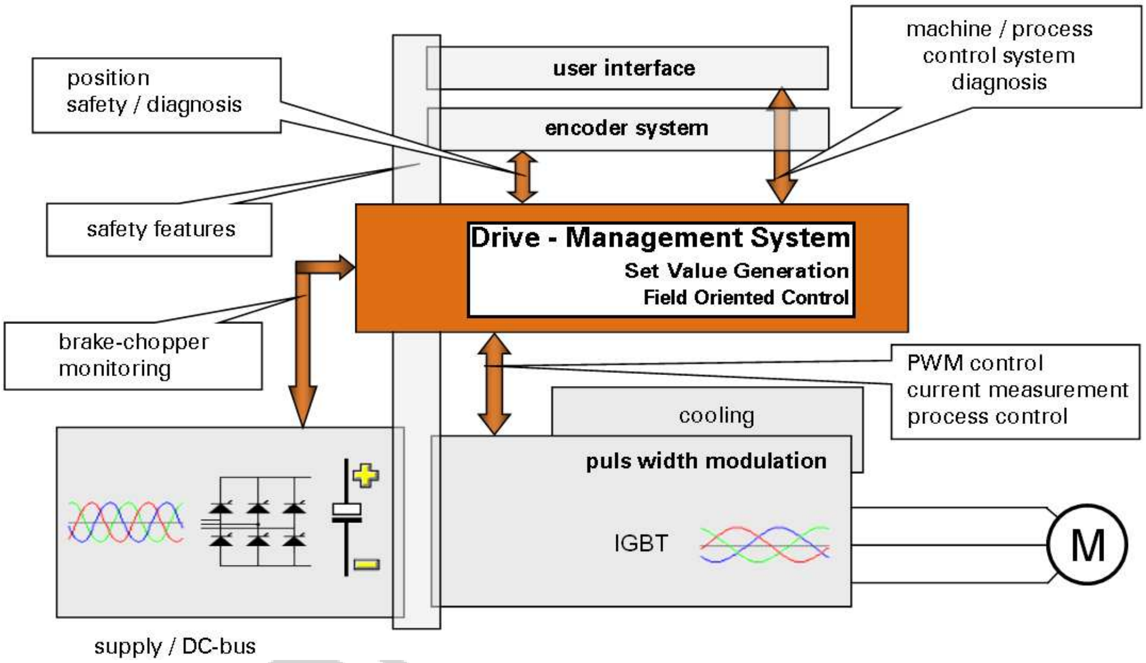


Fig. 42: Power converter, diagram of entire system

The general **control structure of the ACOPOS** is illustrated in the following diagram:

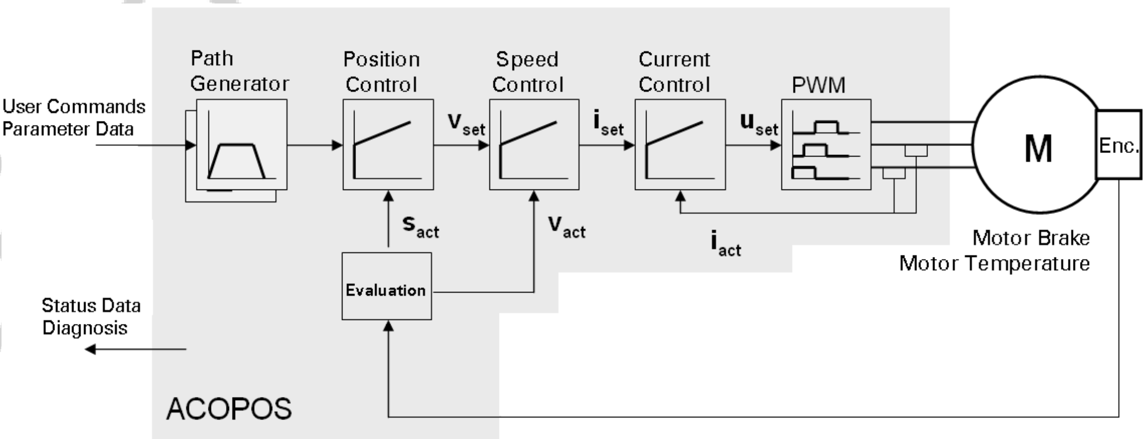


Fig. 43: ACOPOS control structure

Starting from the left, a **path for positioning** is generated based on the user's specifications.

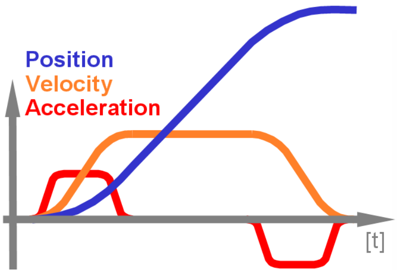


Fig. 44: Positioning profile

The three cascading control loops ...

- Position controller
- Speed controller
- Current controller

... generate a respective **manipulated variable** from their **measurement values** (comparator values) using position and current measurement**.** This is converted to the control signal for the **pulse width modulation**.

The **position encoder** is also integrated here as an important element. It provides the value about the present position (used to derive the speed) of the drive. This information is used as **comparator value for the respective control loop.** This also illustrates the importance of the demand for the highly accurate and high-speed transfer of this information.

A **high-resolution current measurement** is also made. Complex algorithms ensure correct evaluation of the measurements.

The **software,** that handles all of these tasks for the ACOPOS is also considered the **ACOPOS operating system** or **Firmware**. Like any other operating system, the ACOPOS Firmware also manages the resources (memory, interfaces, etc.) of the ACOPOS servo drive.

In addition to the basic components for drive system management (control, parameter management, etc.) the ACOPOS system also has resources that can be allocated by the user.

Function blocks can be configured on the ACOPOS using the application software. This makes it possible perform application-specific calculations or logical decisions on the ACOPOS in an extremely high-speed cycle (400 μs). This allows **maximum specialization** of the system to the demands with a **maximum degree of flexibility.**

3.3.4 Differences between frequency converters and servo drives

As we have already discussed several times, there are clear differences between possibilities offered by a frequency converter and those of a servo drive in the electrical drive technology.

In the previous section, we got an overview of the servo drive's "intelligent components" such as the path generator, measurement systems used to determine the position (encoder system) and application interfaces.

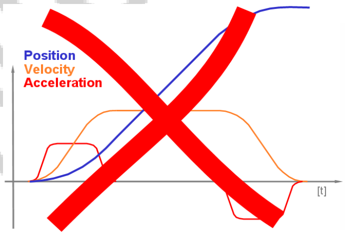
The **frequency converter** however, does not have these mechanisms!

Why then, did we take the time to go over all of these components? We could have covered the topic of frequency converters much earlier, right?

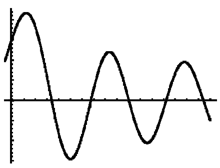
The answer is simple – we now know the important characteristics of the most versatile power converter; the servo drive. From here on out, we are much better prepared to understand and evaluate the **limitations of the frequency converter** as a more basic type of converter.

The conversion of electrical energy from the mains power supply is performed by the power electronics in the frequency converter based on the principle described above.

Unlike a servo drive, the frequency converter is not able to control the motor for a highly-dynamic positioning sequence.



It has a **limited layout** in regard to signal electronics and control. The frequency converter generally converts the voltage from the mains power supply into a voltage with a variable frequency and amplitude.



The power transistors are generally dimensioned smaller than in the servo drive (-> lower overload capacity and dynamic properties).

U/f frequency converter

This is **the most basic design** of a modern frequency converter. The converter regulates the **motor voltage and frequency in a linear relationship.** This results in a very weak torque at low speeds. The speed of the connected motor varies depending on its present load. A current measurement can also be used for compensation (slip compensation) without requiring feedback about the position from a determination of the load. This design is sufficient for simple **applications with small speed variation and without heavy starting**. Only induction motors can be operated.

In the classical sense, a **frequency converter** is basically a **speed positioner:**

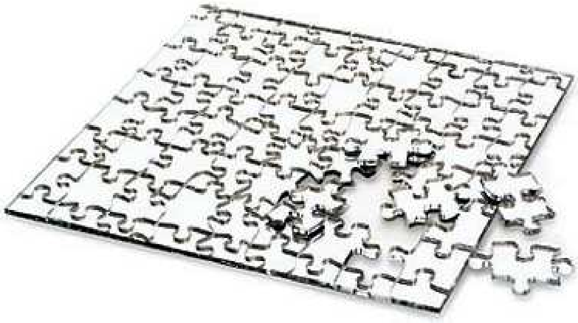
- Rotating field specification without reference to the rotor position (not a position encoder)
- Low PWM switching frequencies
- Slow control response – not suited for dynamic processes
- Dimensioning to rated power without overload properties

The differences between frequency converters and servo drives are evident when making a **direct comparison with one another**:

	Frequency converter	Servo drive
PWM ground frequency	4 ... 8 kHz	5 ... 20 kHz
Current controller	0.5 ... 2 kHz	16 ... 20 kHz
Speed controller	Optional (2 msec)	0.2 ... 1 ms
Position controller	missing	0.4 ... 4 ms
Brake chopper	Optional	Default
Induction motors	Yes	Yes
Synchronous motor	No	Yes
Overload capacity	Low	High
Highly-dynamic movements	No	Yes

4. INTEGRATION IN THE PROCESS

We can recognize the main components of the electronic drive systems from the previous contents. The core characteristics of the individual technologies are also familiar.



In the following section, we will get one more overview summarizing the **important points to consider** when choosing **components**.

The challenge for the software developer is to implement the process in the control program.

4.1 Selecting the technology

The starting point when setting up an electrical drive system is naturally the **process** that must be implemented.

All of the **necessary machine sequences must be exactly known** in order to estimate the mechanical requirements and the **demands placed on the control system** (drive system management, control software):

Power converter

The limitations of the **frequency converter** compared to the servo drive can be seen clearly. Processes that require variable **speed adjustment**, but that **do not require precision positioning or highly dynamic speed profiles** can generally be handled very effectively using a frequency converter.

It is **usually used in combination with an induction motor.** Common applications for this type of configuration include:

- Main spindle drive motors (machine tools, textile spinning machines, packaging machines)
- Conveyor systems with variable speed
- Material transport with variable haul-off speed
- Regulated fan units

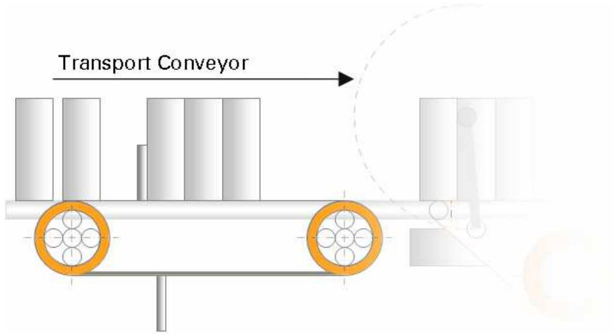


Fig. 45: Conveyor belt

- Simple and cost-effective positioning procedures (very low dynamic properties)

The **servo drive** is used **when higher demands** are placed on positioning in the mechanical system:

- Highly-dynamic movement of precise positioning profiles
- Use of electronic gears with variable gear ratio (positioning in real-time)
- Use of dynamic positioning profiles (cam profiles) for real-time positioning
- Processing of process-specific calculations and logical decisions in one exact cycle (ACOPOS 400 μs)
- Direct measurement of process signals (position encoder, digital inputs) and control of sensors

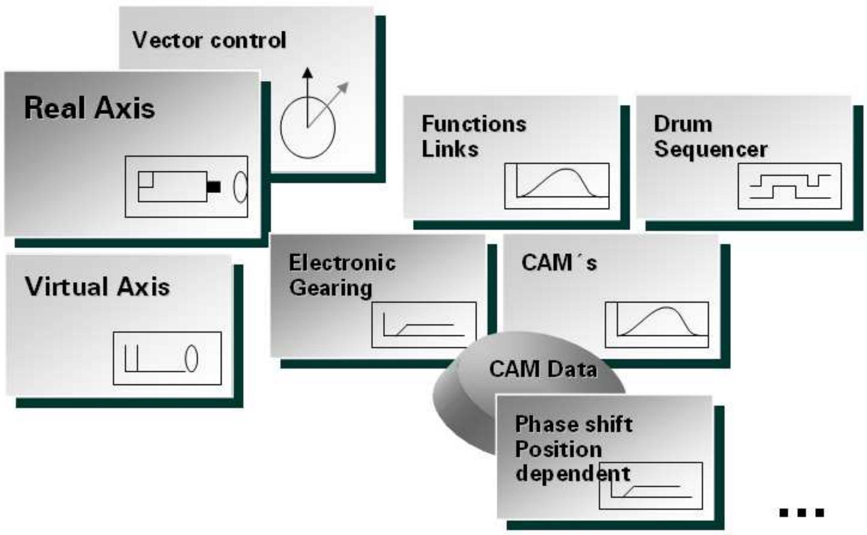


Fig. 46: ACOPOS control software, objects and resources

- Detailed diagnostics possibilities and maximum process control

Motor

The motor is responsible for converting the electrical energy into a movement. It must be able to provide the **torque for positioning** the mechanical system:

$$\boxed{T_{motor} = J_{mech.} \cdot \alpha}$$

T_{motor} ... required drive torque

$J_{mech.}$ ... moment of inertia (mechanical inertia of the entire system)

α ... rotational acceleration (dynamic requirement)

The motor must be designed for both **average load** as well as for the potential **peak loads** (instantaneous accelerations, etc.).

As mentioned many times in the previous sections, a **permanently excited synchronous motor** working together with a servo drive for control is the absolute **front-runner for dynamic and simultaneously precise positioning.**

The B&R product range offers synchronous motor to meet these demands in a wide range of performance:

- Torque from 0.2 – 115 Nm
- Highly dynamic properties
- High peak torque
- Compact construction, high power density
- Low torque ripple
- Reinforced bearings
- Practically maintenance-free

Fig. 47: B&R synchronous motors

Encoder system

One of the main criteria for the position encoder is the **resolution**. It is a decisive factor for how precise positions can ultimately be measured and controlled.

The **quality of drive control** is also largely dependent on the encoder resolution. Additionally, the **speed of position evaluation** and transfer to the servo drive also play a decisive role. In this case, optical encoder systems are superior to the inductive encoder (resolver).

Depending on the application, the constant **repetition of the homing procedure** after a system restart is either not possible or not desirable. In this case, the characteristics of the **extended movement range** of a **multi-turn encoder** can come prove useful.

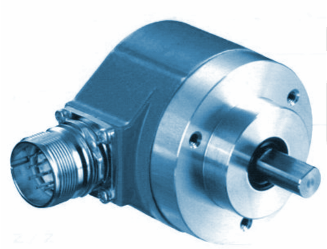


Fig. 48: Position encoder

Physical limits are also defined for safe functioning of the encoder. Above all, **vibrations** and high **temperatures** can cause problems for the encoder. In this case, the resolver is more durable with its highly robust construction. The resolution and control quality offered by the **resolver system** is sufficient for many applications.

B&R servo motors with **ENDAT encoders** and embedded parameter chips make up a compact **plug & play component** for drive automation.

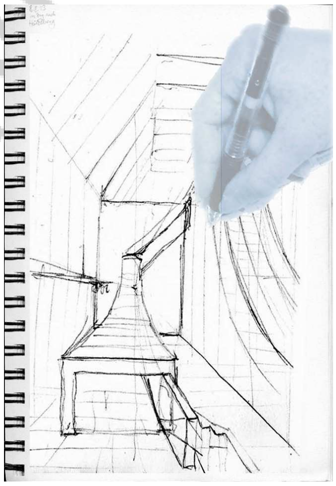
4.2 Developing the control software

As we have seen, modern drive technology encompasses a very wide range of topics, which can and should include a variety of considerations.

The developer of control software is responsible for **implementing the process at hand** in a control program.

Fig. 49: The developer's tasks

It is immensely important to always keep the spectrum of the entire system in mind so that you can plan in all of the aspects accordingly. Only then can the approach be optimally "sketched" and implemented.



The drive system is generally controlled by a CPU that is connected with the servo drive via a communication network (e.g.: ETHERNET-POWERLINK, CAN etc.).

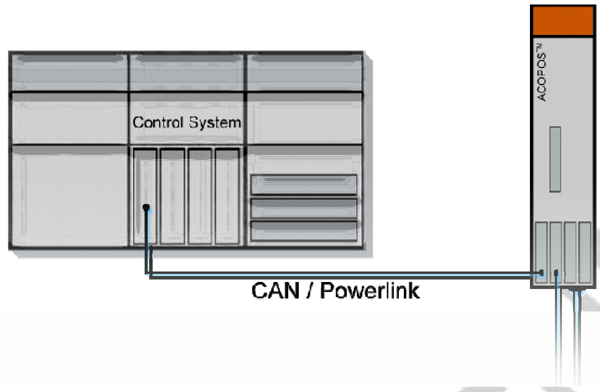


Fig. 50: CPU – ACOPOS communication

The process flow is implemented in the application program. Software tools (graphic editors, etc.) and functions for the control process (positioning commands, etc.) are provided in the development environment (B&R Automation Studio) for this reason.

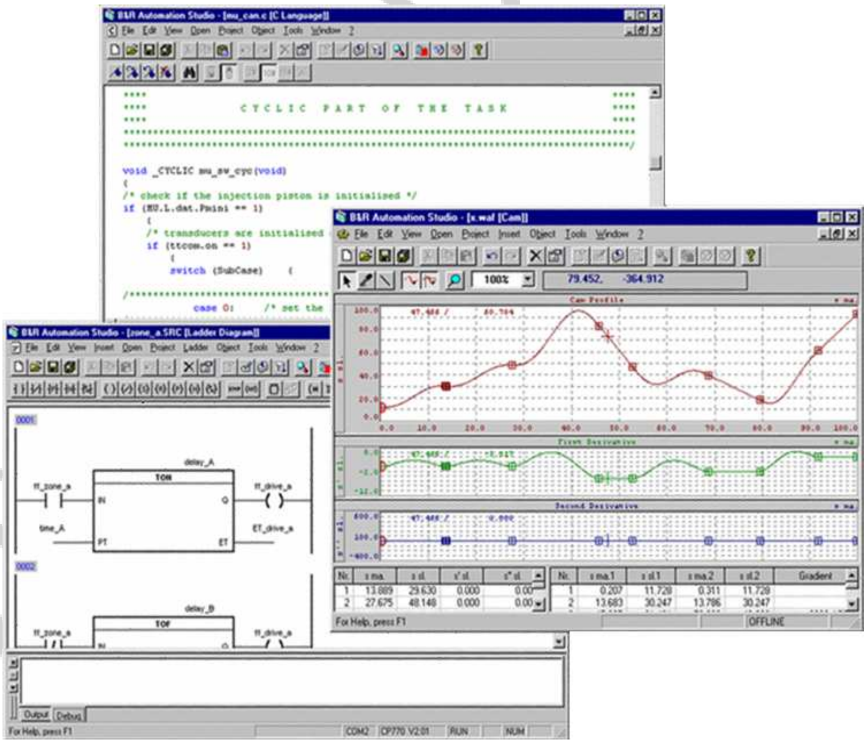


Fig. 51: Automation Studio, Motion Components

The spectrum ranges from simple basic movements...

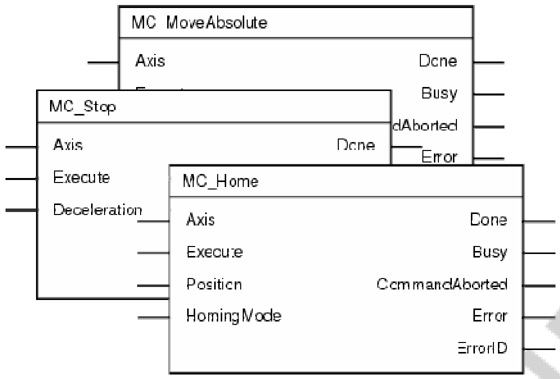


Fig. 52: basic positioning functions

...to the management of dynamic positioning profiles for complex applications.

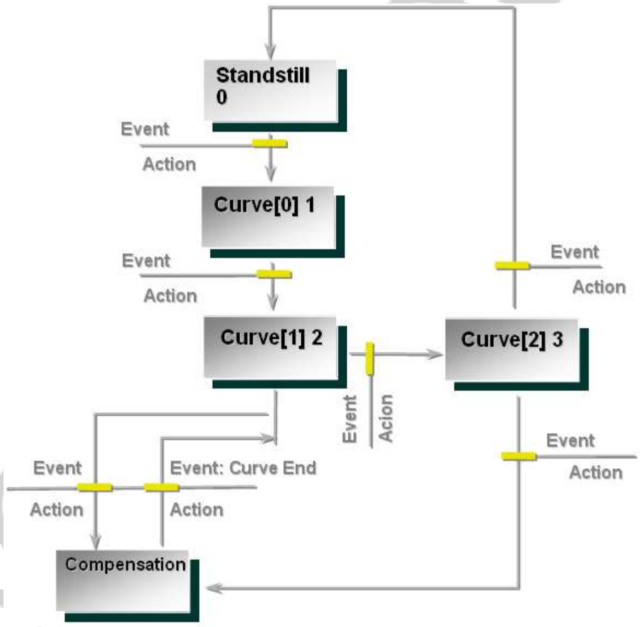


Fig. 53: Cam profile automat

Knowledge of these software-related tools and functions is also important for us so that we can divide the application into individual function units. A modular and structured layout of the control software makes it much easier to create, maintain and expand the software applications.

Note:

The following training modules will deal extensively with the software tools used for setting up and configuring the B&R drive solution.

5. SUMMARY

The level of performance of modern drive systems has improved significantly thanks to technological advancements in the area of power electronics and signal electronics.

Electrical, IT-related and mechanical components are combined to automate a process. Optimum coordination of this mechatronic system is decisive for meeting high demands.

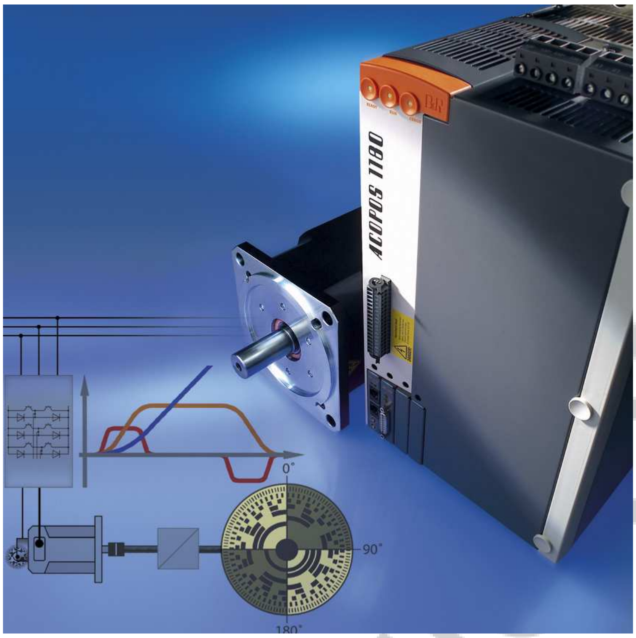


Fig. 54: The fundamentals of the drive system

Even the selection of drive system components must be made in close coordination with the requirements of the process. The specific characteristics of the system components and their effects on the entire system are the main focus in this case.

Basic knowledge about the components, technologies and procedures in the system is quite useful for the software developer.

With this basis, the mechatronic drive system can be optimally adjusted, setup and further developed into a function unit that can be used repeatedly.

Notes

Overview of training modules

TM200 – B&R Company Presentation **
TM201 – B&R Product Spectrum **
TM210 – The Basics of Automation Studio
TM211 – Automation Studio Online Communication
TM212 – Automation Target **
TM213 – Automation Runtime
TM220 – The Service Technician on the Job
TM223 – Automation Studio Diagnostics
TM230 – Structured Software Generation
TM240 – Ladder Diagram (LAD)
TM241 – Function Block Diagram (FBD)
TM246 – Structured Text (ST)
TM247 – Automation Basic (AB)
TM248 – ANSI C
TM250 – Memory Management and Data Storage
TM260 – Automation Studio Libraries I
TM261 – Closed Loop Control with LOOPCONR

TM400 – The Basics of Motion Control
TM410 – The Basics of ASiM
TM440 – ASiM Basic Functions
TM441 – ASiM Multi-Axis Functions
TM445 – ACOPOS ACP10 Software
TM450 – ACOPOS Control Concept and Adjustment
TM460 – Starting up Motors

TM500 – The Basics of Integrated Safety Technology
TM510 – ASiST SafeDESIGNER

TM600 – The Basics of Visualization
TM610 – The Basics of ASiV
TM630 – Visualization Programming Guide
TM640 – ASiV Alarm System
TM650 – ASiV Internationalization
TM660 – ASiV Remote
TM670 – ASiV Advanced

TM700 – Automation Net PVI
TM710 – PVI Communication
TM711 – PVI DLL Programming
TM712 – PVIServices
TM730 – PVI OPC

TM800 – APROL System Concept
TM810 – APROL Setup, Configuration and Recovery
TM811 – APROL Runtime System
TM812 – APROL Operator Management
TM813 – APROL XML Queries and Audit Trail
TM830 – APROL Project Engineering
TM840 – APROL Parameter Management and Recipes
TM850 – APROL Controller Configuration and INA
TM860 – APROL Library Engineering
TM865 – APROL Library Guide Book
TM870 – APROL Python Programming
TM890 – The Basics of LINUX

**) see Product Catalog

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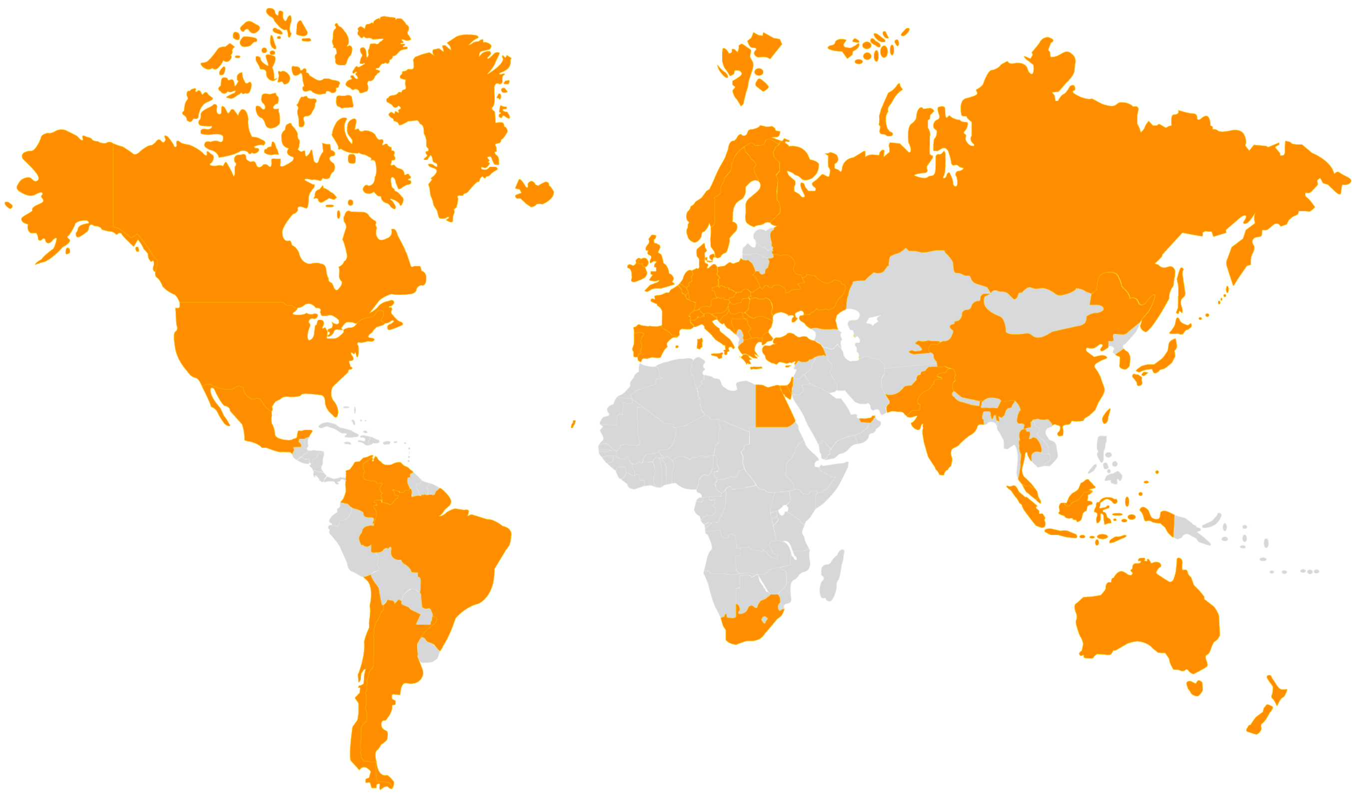

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