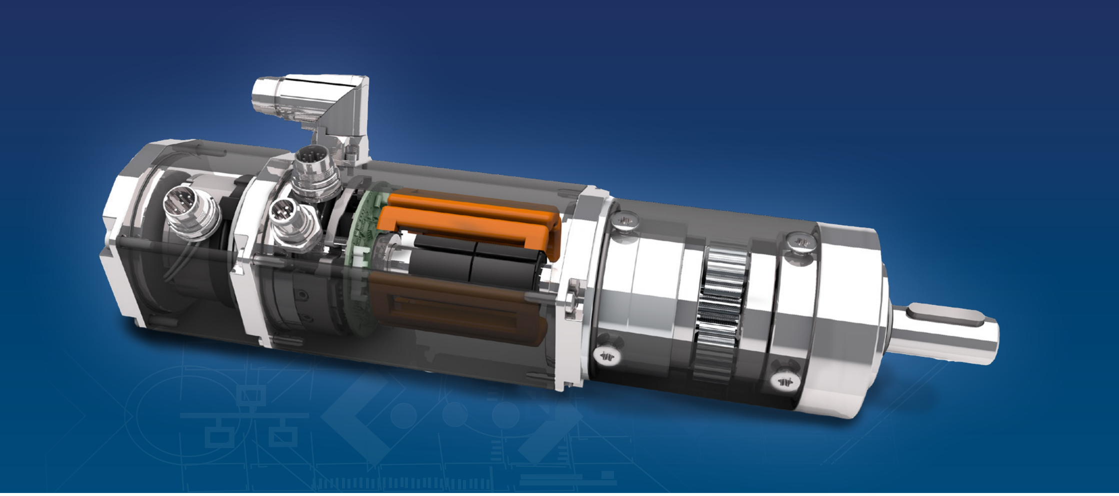
Handbook

for selection of motors



Editorial

Dunkermotoren GmbH is an internationally operating company and a leader in the field of low-power electrical motors. Dunkermotoren GmbH offers a wide range of gearboxes and electrical motors based on a sophisticated modular system.

In combination with many years of experience in development, manufacturing and design of electrical motors Dunkermotoren GmbH presents itself as a supplier of simple electric motors as well as a partner for the realization of complex motor technologies.

The current formulary was created by specialists to support users of electrical motors. It helps to understand electrical motors in their application and assists in the selection of motor components. The systematic set-up of the formulary facilitates the introduction into the subject matter and makes this formulary a valuable tool for apprentices, students, career beginners and experienced professionals. The breadth of motor components and solutions considered satisfies the requirements of engineers who have to design, select or adapt their motors in their daily work.
For practitioners, the collection of examples serves as a guide for their own calculations, thus facilitating the application of the formulas for real design tasks.

Electrical motors are continually evolving, and so the present formulary is subject to constant revision. If you miss any content or have suggestions and wishes for future editions of the formulary, we are looking forward to your feedback.

Your Dunkermotoren GmbH

Content

1 Systematic

Electrical motors consist of a variety of components which are to be treated mathematically.

- The gearbox is a mechanical converter. It adjusts the physical quantities, such as the speed and the torque, delivered by the motor to the requirements of the working machine.
- The electrical motor serves as an energy converter which converts the electrical energy supplied into mechanical energy.
- The motor encoder detects actual motion variables such as speed, velocity, position and makes them available to the signal electronics.
- The brake prevents movement of the motor when the control unit is switched off.
- The control unit is an electric energy converter and controls the motion variables of the electrical motor.

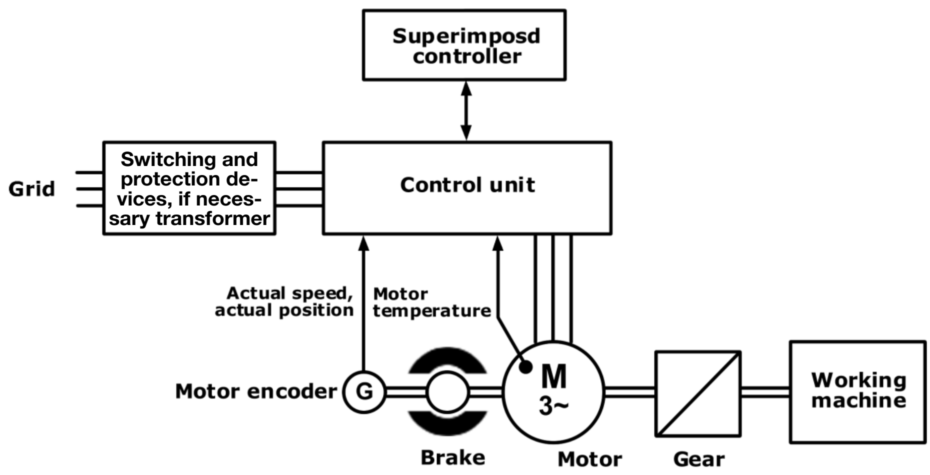
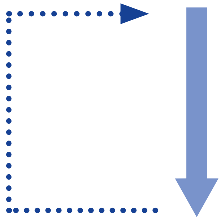


Figure 1 Components of an electrical motor

The sequence in which the individual components are considered is based on the procedure for the design of electrical motors. It is carried out in steps which build on each other and, starting from the working machine, passes through all components of the electrical motor.



1. Selection of the optimum motor technology
2. Definition of the motion sequence and the load
3. Selection of the gear
4. Selection of the motor and the encoder
5. Selection of the control unit
6. Check of the costs and, if necessary, repeating steps 1 to 6 with another motor technology

Figure 2 Procedure for the design of electrical motors

2 Selection of the optimum motor technology

2.1 Overview of possible motor technologies

2.1.1 Classification by application

For the design of electrical motors, it is helpful to classify them into three categories with regard to the requirements for speed adjustability.

Constant speed motors	Variable speed motors	Servo motors
Constant speed motors are operated at a fixed speed. They only have facilities for switching on and off, as well as for protection against overload. There is no speed adjustment device. Typical applications » Pumps » Fans » Conveyors	Variable speed motors are adjustable in their speed. In addition to the electrical motor, they have a control unit that is responsible for the speed adjustment. Typical applications » Trolleys » Hoists » Conveyors » Pull motors and winders for continuous webs (film, paper, textile fibres, wire)	Servo motors are designed to perform positioning tasks. They have a high acceleration capability and a high overload capacity. In addition to the electrical motor (servomotor), they have a control unit and position sensor (closed loop). Typical applications » Door motors » Motors in packaging and filling machines » Feed motors in machine tools » Robot motors

Table 1 Classification of electrical motors with regard to speed adjustability

2.1.2 Classification by operational quadrant

Electrical motors have the ability of reversing the direction of rotation and the ability of energy recovery. These characteristics of an electrical motor are shown in a speed-torque diagram. Depending on the sign of the speed and the torque, four operating quadrants result.

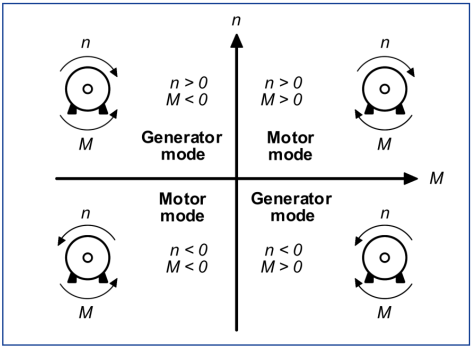


Figure 3 Operational quadrants of electrical motors

In motor mode quadrants, the speed and torque of the motor have the same direction. In generator mode quadrants, the speed and the torque are directed in opposite directions. As a positive direction of rotation, the clockwise rotation is defined with respect to the motor shaft. Depending on the design of the control unit, electrical motors operate only in the first quadrant (e.g. pumps) or in all four quadrants (e.g. hoists).

2.1.3 Classification according to technical realisation

Electrical motors are offered in various designs, each with specific strengths and weaknesses as well as preferred power ranges. Taking into account the different characteristics of control units, a large number of motor technologies are produced.

According to the shape of the motor current, DC motors and 1-phase or 3-phase AC-motors are distinguished:

DC motors use a DC motor. For smaller motors, the required magnetic field is generated with permanent magnets. These DC motors can be operated both at a constant DC voltage as well as at pulse converters.

AC motors use motors that are operated with 1-phase or 3-phase AC current. The frequency of the motor current has a decisive influence on the motor speed. Synchronous motors follow in their rotary motion exactly the frequency of the feeding current. They are always operated with a control unit. In practice, synchronous motors of smaller design are often referred to a brushless DC motors.

Depending on the shape of the current flowing in the motor windings, synchronous motors are divided in motors with block commutation and motors with sinusoidal commutation.

At asynchronous motors a difference between the frequency of the motor current and the rotational frequency occurs. They can be operated either directly on the AC grid as well as on actuators.

If a motor is operated on a control unit, the control unit decides on the possibility and quality of the speed adjustability. Simple control units such as frequency converters or commutation electronics enable speed changes within the range of seconds. High-performance control units (e.g. servo controllers) adjust the motor position and speed very precisely within a few milliseconds.

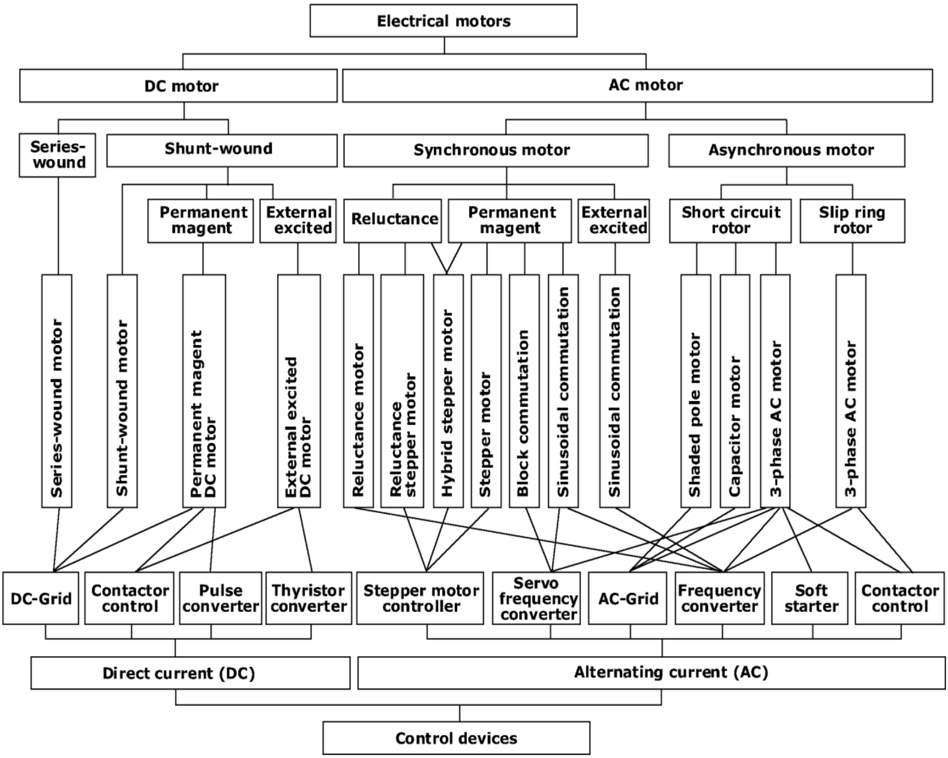


Figure 4 Motor technologies

2.2 Selection of the optimum motor technology

From the theoretically available motor technologies, the optimum motor technology has to be selected and subsequently dimensioned.

The suitable motor technology can easily be selected by using table 2 which contains all motor technologies that may be considered.

The form allows the selection in two steps:
In the first step, all the motor technologies which cannot meet the technical requirements of the application are eliminated. Technical exclusion criteria are used for this purpose. If a motor technology can not cover these criteria, it is excluded for the second step.
In the upper part of Table 2 for each exclusion criterion it is marked, if the motor technology meets the criterion (table field marked with an "x"), or if it doesn't (table field is empty).

In the second step, the remaining motor technologies are compared with each other and the optimum solution is determined. Performance criteria are used for this. In the lower part of Table 2, for each performance criterion it is indicated, how the motor technology satisfies the criterion (table field is filled with a corresponding performance number). The following exclusion criteria are used:

Application

The applications according to chapter 1 (constant speed motor, variable speed motor, servo motor) cannot be implemented with all motor technologies.

Power range

Motor technologies are only available in certain power range. If the application requires a different power range, the motor technology cannot be used.

Start-up

If the motor starts up against a high load, some motor technologies are not applicable and have to be deselected.

Power supply

Constant speed motors in particular can only be operated with the appropriate power supply. Depending on the available power supply network certain motor technologies have to be excluded.

To exclude technical unsuitable motor technologies select in the upper part of Table 2 in the second column the criteria valid for the application. Then, go to the right in each selected row and deselect all columns that are not marked with "x". The motor technologies in the deselected columns do not have to be considered for the second selection step. The following performance criteria are used:

Small motor size

Depending on the type of motor, different sizes can be obtained with comparable power.

High speed accuracy and high dynamics

Depending on the design of the control unit, the motor technologies differs in their ability to set the speed precisely and dynamically.

Low grid perturbation

Depending on the presence of a control device, the motor technologies load the power supply network during start-up with a high or low start-up current.

Low cost

The motor technologies have different costs because of the different types of motor and control unit.

Low complexity

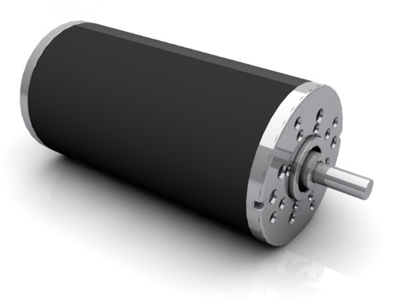
Depending on the design, the motor technologies are more or less complex and create different requirements on the skills of the maintenance stuff.

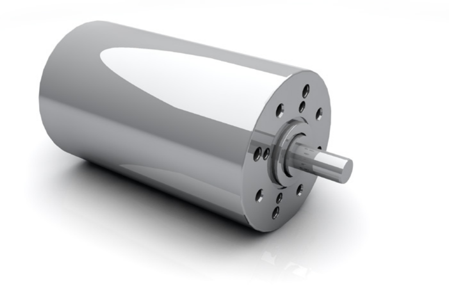
Long lifetime, low maintenance efforts

Depending on the motor type, the motor technology is low-maintenance and has a long lifetime.

To select the optimum motor technology you define the priorities of the performance criteria for the application under consideration in the lower part of Table 2 in the second column. If the criterion is very important to you, set the value to 10. If the criterion is unimportant, enter 0 for the priority. Then, move to the right in each selected row and multiply the priority by the performance number and enter the resulting score into the corresponding field.

If, for all technically suitable motor technologies, the scores for all performance criteria are determined, add these columns to a total score. The motor technology with the highest overall score is the optimum motor technology that should be selected for the application under consideration.





			Series-wound DC motor on DC grid	Shunt-wound DC motor on DC grid	Shunt-wound DC motor on DC gridwith start-up resistor	Permanent magent DC motor (GR) on DC grid	Permanent magent DC motor with pulse converter and open loop voltage control (GR)	Permanent magent DC motor with pulse converter and closed loop control (GR)	External excited DC motorwith power converter	Reluctance motor on frequency converterwith V/f-Control	Stepper motor with control device	Brushless DC motor (BG)with power electronics and open loop V-Control
Exclusion criteria	Application											
	x	Constant speed motor	x	x	x	x						x
		Variable speed motor					x	x	x	x	x	x
		Servo motor						x	x	x	x	
	Power rangeGrid											
		< 100 W	x			x	x	x		x	x	x
		< 1 kW		x	x	x	x	x	x	x	x	x
		< 50 kW		x	x	x	x	x	x	x		
		< 500 kW							x			
		> 500 kW							x			
	Start-up											
		Without or with low load	x	x	x	x	x	x	x	x	x	x
		With load	x	x	x	x	x	x	x			x
	Grid											
		DC-grid	x	x	x	x	x	x		x	x	x
		1-phase AC grid					x	x	x	x		
		3-phase AC grid					x	x	x	x		
	Suitability											
Performance criteria	Features											
	3	Small size	1	1	1	4	4	4	1	2	2	15
		High speed accuracy and high dynamics	0	0	0	0	2	5	3	3	2	2
		Low grid disturbances	0	[illegible]	[illegible]	[illegible]	[illegible]	2	2	2	2	2
		Low cost	4	4	3	5	4	3	1	4	4	4
		Low complexity	5	5	4	5	3	2	2	3	3	4
		Long life time, low maintenance efforts	0	0	0	1	1	1	[illegible]	[illegible]	[illegible]	[illegible]
	Ranking											34

Available motor technologies

Motor technology does not cover exclusion criterion

Motor technology covers exclusion criterion

Selection of the required exclusion criteria
Choose one for each criterion.

Priority of performance criteria
0: not important to
10: very important

Enter product from priority and performance number

Enter the sum of the points

Table 2 Form for selecting the optimum motor technology

Brushless DC motor with servo amplifier (BGE/DME)	Brushless DC motor (BG)with in-tegrated power electronics dMove	Permanent magnet synchronous mo-tor with sinusoidal commutation (BG) and integrated servo amplifier dPro	External excited synchronous motor with sinusoidal commuation and frequency converter	Capacitor motor on AC grid	Shaded pole motor on AC grid	Universal motor on AC grid	3-phase asynchronous motor on AC grid (DR)	3-phase asynchronous motor on AC gridwith soft starter (DR)	3-phase asynchronous motor on AC gridwith star-delta start-up (DR)	3-phase asynchronous motor on frequency converter with V/f-Control	3-phase asynchronous motor on frequency converter with vector control	3-phase asynchronous motor with servo frequency converter	3-phase asynchronous motor with slip ringson AC grid with resistor start-up
	x	x		x	x	x	x	x	x	x	x	x	x
x	x	x	x							x	x	x	
x	x	x										x	
x	x	x		x	x	x	x						
x	x	x		x		x	x	x	x	x	x	x	x
x		x	x				x	x	x	x	x	x	x
			x					x	x		x	x	
			x					x			x		
x	x	x	x	x	x	x	x	x	x	x	x	x	x
x	x	x	x							x	x	x	x
x	x	x								x	x	x	
x				x	x	x				x	x	x	
x			x				x	x	x	x	x	x	x
5	Performance number		3	2	2	2	2	2	2	2	2	3	3
5	3	5	4	0	0	0	0	0	0	2	3	4	0
2	2	2	2	0	0	0	0	1	1	2	2	2	1
1	2	1	0	5	5	4	5	4	4	3	3	2	3
1	3	2	1	5	5	5	5	4	4	3	2	0	4
5	5	5	0	5	5	0	5	5	5	5	5	5	0

Continuation Table 2

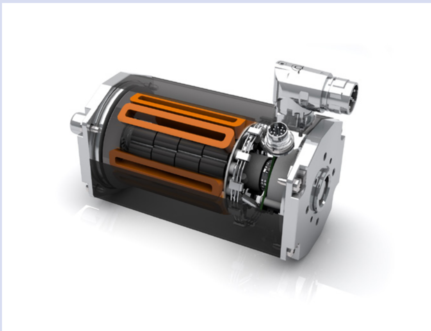
2.3 Electrical motors from Dunkermotoren

2.3.1 Permanent Magnet DC Motors - Series GR

Brush type commutated DC motors from Dunkermotoren are notable for robust and maintenance-free design, longer life-time than commutated motors from other manufacturers, motor insulation class E, extremely high short time overload capacity of the motor and especially high quality due to fully automated production lines. The DC motors can be combined with control electronics, gearboxes, brakes and encoders in a modular system to provide flexible, adaptable, market-oriented solutions.

2.3.2 Brushless DC Motors - Series BG

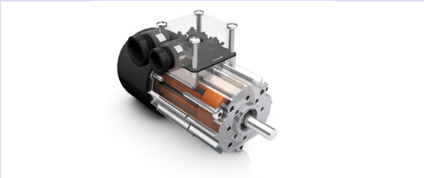
Brushless motors (EC motors) from Dunker-motoren are notable for very high lifetime, high efficiency, dynamic acceleration, robust design, high overload capability and protec-tion class up to IP65. Combined in a modular system with control gearboxes, brakes and encoders, these electronically commutated DC motors provide a flexible, adaptable, market-oriented solution. Following electro-nic variants are available:



- » ***dCore*** integrated hall sensors
- » ***dGo*** integrated commutation electronics
- » ***dMove*** integrated controller for speed- and current control operation, control through field bus or I/Os
- » ***dPro*** Integrated sinusoidal servo controller and integrated high resolution encoders for speed- positioning- and current control operation, control through field bus, industrial Ethernet, I/Os or stand-alone operation

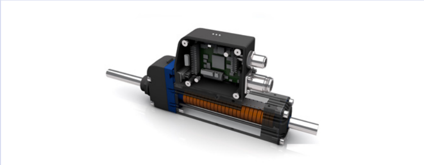
2.3.3 Asynchronous AC Motors - Series KD/ DR

Dunkermotoren offers single-phase AC motors of the series KD and three-phase AC motors of the series DR. The motors can be combined with brakes and gearboxes.



2.3.4 Linear Systems - Series ST | CASM | LS

Dunkermotoren offers a wide spectrum of linear motor technology. Whether direct tubular linear motors for highly dynamic positioning tasks or spindle systems with thrust forces in the range of kilo Newton.



2.4 Example: Pump motor

The form for selecting the optimum motor technology is applied to a pump motor. The following requirements are specified for the pump motor:

Operating conditions:	Series application in heating systems, long lifetime, maintenance-free, easy handling by service technicians
Power supply:	DC 24 V
Power range:	Approx. 50 W
Speed adjustment:	Not required

In the **first step**, the technically suitable motor technologies are extracted. According to table 5, the following motor technologies are usable:

- Series wound DC motor on DC grid
- Permanent magnet DC motor (GR) on DC grid
- Brushless DC motor (BG) with power electronics and open loop V-Control
- Brushless DC motor (BG) with integrated power electronics ***dMove***
- Permanent magnet synchronous motor with sinusoidal commutation (BG) and integrated servo amplifier ***dPro***

For the **second step**, the requirements of the application are weighted and the priorities are assigned:

Performance criterion	Priority	Reason
Small size of the motor	1	This is of little importance for this application.
High speed accuracy and high dynamics	3	Accuracy and dynamics are not very important for pumps in general.
Low grid perturbation	1	Since the power is relatively small, grid perturbation due to start-up processes are hardly to be expected.
Low cost	10	Since it is a standard application, low costs for motor technology are very important.
Low complexity	8	Easy handling is expressly required.
Long lifetime, low maintenan-ce efforts	10	Maintenance-free operation is expressly required.

Table 3 Prioritisation of the performance criteria for selecting the optimum motor technology for a pump motor

This results in the following scores for the suitable motor technologies:

Motor technology	Score
Series-wound DC motor on DC grid	81
Permanent magnet DC motor (GR) on DC grid	104
Brushless DC motor (BG) with power electronics and open loop V-Control	**135**
Brushless DC motor (BG) with integrated power electronics ***dMove***	110
Permanent magnet synchronous motor with sinusoidal commutation (BG) and integrated servo amplifier ***dPro***	98

Table 4 Ranking of motor technologies for a pump motor

The optimum motor technology is thus the brushless DC motor (BG) with power electronics and open loop V-Control.

2.5 Example: Door motor

The form for selecting the optimum motor technology is subsequently applied to a motor for an elevator door. The following basic conditions are given for the door motor:

The form for selecting the optimum motor technology is subsequently applied to a motor for an elevator door. The following basic conditions are given for the door motor:
Operating conditions: Series application, elevator doors in the living area, small installation space for engine and gearbox required, maintenance-free, handling by trained service technicians

Power supply:	DC 24 V
Power range:	Approx. 200 W
Speed adjustment:	Positioning function required

In the **first step**, the technically suitable motor technologies are extracted. According to Table 8, the following motor technologies are usable:

- Permanent magnet DC motor with pulse converter and closed loop control (GR)
- Brushless DC motor with servo amplifier (BGE/DME)
- Brushless DC motor (BG) with integrated power electronics ***dMove***
- Permanent magnet synchronous motor with sinusoidal commutation (BG) and integrated servo amplifier ***dPro***
- 3-phase asynchronous motor with servo frequency converter

For the **second step**, the requirements of the application are weighted and the priorities are assigned:

Performance criterion	Priority	Reason
Small size of the motor	5	The small size is important.
High speed accuracy and high dynamics	8	Accuracy and dynamics are very important for positioning motors.
Low grid perturbation	2	Grid perturbation due to start-up is less relevant.
Low cost	9	Since it is a series application, low costs for the motor technology are very important
Low complexity	2	Handling by trained service technicians.
Long lifetime, low maintenance efforts	3	Maintenance-free operation is required.

Table 6 Prioritisation of the performance criteria for selecting the optimum motor technology for a door motor

This results in the following scores for the suitable motor technologies:

Motor technology	Score
Permanent magnet DC motor with pulse converter and closed loop control (GR)	**98**
Brushless DC motor with servo amplifier (BGE/DME)	95
Brushless DC motor (BG) with integrated power electronics ***dMove***	92
Permanent magnet synchronous motor with sinusoidal commutation (BG) and integrated servo amplifier ***dPro***	97
3-phase asynchronous motor with servo frequency converter	84

Table 7 Ranking of motor technologies for a door motor

			Series-wound DC motor on DC grid	Shunt-wound DC motor on DC grid	Shunt-wound DC motor on DC gridwith start-up resistor	Permanent magent DC motor (GR) on DC grid	Permanent magent DC motor with pulse converter and open loop voltage control (GR)	Permanent magent DC motor with pulse converter and closed loop control (GR)	External excited DC motorwith power converter	Reluctance motor on frequency converterwith V/f-Control	Stepper motor with control device
Exclusion criteria	Application										
	x	Constant speed motor	x	x	x	x	—	—	—	—	—
		Variable speed motor					x	x	x	x	x
		Servo motor						x	x	x	x
	Power range										
	x	< 100 W	x	—	—	x	x	x	—	x	x
		< 1 kW		x	x	x	x	x	x	x	x
		< 50 kW		x	x	x	x	x	x	x	
		< 500 kW							x		
		> 500 kW							x		
	Start-up										
	x	Without or with low load	x	x	x	x	x	x	x	x	x
		With load	x	x	x	x	x	x	x		
	Energieversorgungsnetz										
	x	DC-grid	x	x	x	x	x	x	—	x	x
		1-phase AC grid					x	x	x	x	
		3-phase AC grid					x	x	x	x	
	Suitability										
Performance criteria	Features										
	1	Small size	**1**	1	1	**4**	4	4	1	2	2
	3	High speed accuracy and high dynamics	**0**	0	0	**0**	2	5	3	3	2
	1	Low grid disturbances	**0**	0	1	**0**	2	2	2	2	2
	10	Low cost	**40**	4	3	**50**	4	3	1	4	4
	8	Low complexity	**40**	5	4	**40**	3	2	2	3	3
	10	Long life time, low maintenance efforts	**0**	0	0	**10**	1	1	0	5	5
	Ranking		**81**			**104**					

Table 5 Form for selecting the optimum motor technology for a pump motor

Brushless DC motor (BG)with power electronics and open loop V-Control	Brushless DC motor with servo amplifier (BGE/DME)	Brushless DC motor (BG)with in-tegrated power electronics dMove	Permanent magnet synchronous mo-tor with sinusoidal commutation (BG) and integrated servo amplifier dPro	External excited synchronous motor with sinusoidal commuation and frequency converter	Capacitor motor on AC grid	Shaded pole motor on AC grid	Universal motor on AC grid	3-phase asynchronous motor on AC grid (DR)	3-phase asynchronous motor on AC gridwith soft starter (DR)	3-phase asynchronous motor on AC gridwith star-delta start-up (DR)	3-phase asynchronous motor on frequency converter with V/f-Control	3-phase asynchronous motor on fre-quency converter with vector control	3-phase asynchronous motor with servo frequency converter	3-phase asynchronous motor with slip ringson AC grid with resistor start-up
x	—	x	x	—	x	x	x	x	x	x	x	x	x	x
x	x	x	x	x							x	x	x	
	x	x	x										x	
x	x	x	x	—	x	x	x	x	—	—	—	—	—	—
x	x	x	x		x		x	x	x	x	x	x	x	x
	x		x	x				x	x	x	x	x	x	x
				x					x	x		x	x	
				x					x			x		
x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
x	x	x	x	x							x	x	x	x
x	x	x	x	—	—	—	—	—	—	—	x	x	x	—
	x				x	x	x				x	x	x	
	x			x				x	x	x	x	x	x	x
5	5	**5**	**5**	3	2	2	2	2	2	2	2	2	3	3
6	5	**9**	**15**	4	0	0	0	0	0	0	2	3	4	0
2	2	**2**	**2**	2	0	0	0	0	1	1	2	2	2	1
40	1	**20**	**10**	0	5	5	4	5	4	4	3	3	2	3
32	1	**24**	**16**	1	5	5	5	5	4	4	3	2	0	4
50	5	**50**	**50**	0	5	5	0	5	5	5	5	5	5	0
135		**110**	**98**											

Continuation Table 5

			Series-wound DC motor on DC grid	Shunt-wound DC motor on DC grid	Shunt-wound DC motor on DC gridwith start-up resistor	Permanent magent DC motor (GR) on DC grid	Permanent magent DC motor with pulse converter and open loop voltage control (GR)	Permanent magent DC motor with pulse converter and closed loop control (GR)	External excited DC motorwith power converter	Reluctance motor on frequency converterwith V/f-Control	Stepper motor with control device
Exclusion criteria	Application										
		Constant speed motor	x	x	x	x					
		Variable speed motor					x	x	x	x	x
	x	Servo motor	—	—	—	—	—	x	x	x	x
	Power range										
		< 100 W	x			x	x	x		x	x
	x	< 1 kW	—	x	x	x	x	x	x	x	x
		< 50 kW		x	x	x	x	x	x	x	
		< 500 kW							x		
		> 500 kW							x		
	Start-up										
		Without or with low load	x	x	x	x	x	x	x	x	x
	x	With load	x	x	x	x	x	x	x	—	—
	Grid										
	x	DC-grid	x	x	x	x	x	x	—	x	x
		1-phase AC grid					x	x	x	x	
		3-phase AC grid					x	x	x	x	
	Suitability										
Performance criteria	Features										
	5	Small size	1	1	1	4	4	**20**	1	2	2
	8	High speed accuracy and high dynamics	0	0	0	0	2	**40**	3	3	2
	2	Low grid disturbances	0	0	1	0	2	**4**	2	2	2
	9	Low cost	4	4	3	5	4	**27**	1	4	4
	2	Low complexity	5	5	4	5	3	**4**	2	3	3
	3	Long life time, low maintenance efforts	0	0	0	1	1	**3**	0	5	5
	Ranking							**98**			

Table 8 Form for selecting the optimum motor technology for a door motor

Brushless DC motor (BG)with power electronics and open loop V-Control	Brushless DC motor with servo amplifier (BGE/DME)	Brushless DC motor (BG)with integrated power electronics dMove	Permanent magnet synchronous motor with sinusoidal commutation (BG) and integrated servo amplifier dPro	External excited synchronous motor with sinusoidal commuation and frequency converter	Capacitor motor on AC grid	Shaded pole motor on AC grid	Universal motor on AC grid	3-phase asynchronous motor on AC grid (DR)	3-phase asynchronous motor on AC gridwith soft starter (DR)	3-phase asynchronous motor on AC gridwith star-delta start-up (DR)	3-phase asynchronous motor on frequency converter with V/f-Control	3-phase asynchronous motor on frequency converter with vector control	3-phase asynchronous motor with servo frequency converter	3-phase asynchronous motor with slip ringson AC grid with resistor start-up
x		x	x		x	x	x	x	x	x	x	x	x	x
x	x	x	x	x							x	x	x	
—	x	x	x	—									x	—
x	x	x	x		x	x	x	x						
x	x	x	x	—	x	—	x	x	x	x	x	x	x	x
	x		x	x				x	x	x	x	x	x	x
				x					x	x		x	x	
				x					x			x		
x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
x	x	x	x	x	—						x	x	x	x
x	x	x	x	—							x	x	x	—
	x				x	x	x				x	x	x	
	x			x				x	x	x	x	x	x	x
5	**25**	**25**	**25**	3	2	2	2	2	2	2	2	2	**15**	3
2	**40**	**24**	**40**	4	0	0	0	0	0	0	2	3	**32**	0
2	**4**	**4**	**4**	2	0	0	0	0	1	1	2	2	**4**	1
4	**9**	**18**	**9**	0	5	5	4	5	4	4	3	3	**18**	3
4	**2**	**6**	**4**	1	5	5	5	5	4	4	3	2	**0**	4
5	**15**	**15**	**15**	0	5	5	0	5	5	5	5	5	**15**	0
	95	**92**	**97**										**84**	

Continuation Table 8

3 Description of the load cycle

3.1 Kinematic equations

The load cycle of an application is described by the chronological sequence of the motion and force variables. If the movement is cyclically, only one period is considered.

Mathematically it is necessary to distinguish between translational and rotational movements. As a matter in fact, this distinction is often not made. In particular the terms position (for distance and angle), speed, acceleration and jerk are used for both types of movement.

The movement of bodies is described by the following kinematic equations.

Translation			Rotation		
s:	Distance	$s = f(t)$	φ:	Angle	$\varphi = f(t)$
v:	Velocity	$v = \frac{ds}{dt}$	ω:	Angular speed	$\omega = \frac{d\varphi}{dt}$
			n:	Speed (1/s)	$n = \frac{\omega}{2\pi}$
a:	Acceleration	$a = \frac{dv}{dt}$	α:	Angular acceleration	$\alpha = \frac{d\omega}{dt}$
j:	Jerk	$j = \frac{da}{dt}$	ρ:	Angular jerk	$\rho = \frac{d\alpha}{dt}$

Table 9 Kinematic equations of translation and rotation

The movements of the bodies are caused by forces which act upon them. The relationship between force and motion results from the set of Newton or its extension to the force and /or torque equilibrium.

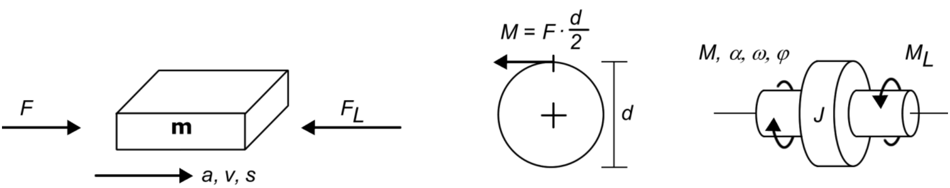


Figure 5 Forces and torques

The forces and torques provided by the electrical motor are used
- for acceleration and deceleration of the mechanical elements
- for compensation of the load forces and load torques required by the working machine.

Translation			Rotation		
F:	Force		M:	Torque	$M = F \cdot \frac{d}{2}$
F:	Force equilibrium	$F = F_B + F_L$	M:	Torque equilibrium	$M = M_B + M_L$
F_B:	Acceleration force	$F_B = m \cdot a$	M_B:	Acceleration torque	$M_B = J\frac{d\omega}{dt}$
F_L: M_L: m:	Load force Load torque Mass of linear moving mechanical elements		J: d:	Moment of inertia of rotating mechanical elements Diameter at which the load force engages	

Table 10 Force and torque equilibrium

In order to be able to use the force and torque equations,

- the movement sequence,
- the masses and moments of inertia to be moved and
- the applied load forces and load torques

have to be known. Their investigation is the subject of the following chapters.

3.2 Motion laws

3.2.1 Motion laws for constant speed motors

The motion of constant speed motors is determined by the On and Off commands which the motor receives from the superimposed controller or directly from the operator.

At the beginning of each change in state, a start-up or a ramp-down occurs. During the (continuous) operation, the operating point is determined by the load. The speed of the motor depends on the load. There is no active influence on the motion variables. The power the motor has to apply during continuous operation is often used as selection criteria. The duration of the entire load cycle for constant speed motors is practical in the range of minutes or hours. The distances or revolutions the motors move forward are theoretically unlimited. Constant speed motors are therefore designed with rotary motors.

3.2.2 Motion laws for variable speed motors

The motion of variable speed motors is defined by the time profile of the speed. Speed changes are carried out with a maximum permissible acceleration.

By slow changes of the speed, for example, the tilting of objects on conveyor belts and vehicles, the tearing of webs, sudden pressure changes in pipelines shall be prevented.

In the case of variable speed motors, the acceleration and deceleration processes are slow. So the acceleration of the mechanical elements has only a very small influence on the required motor torque. The duration of the entire load cycle is practical in the range of minutes or hours. The distances or revolutions the motors move forward are theoretically unlimited. Therefore variable speed motors are designed with rotary motors.

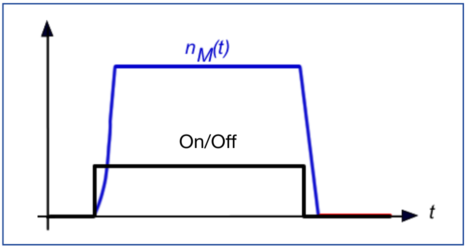


Figure 6 Speed profile of a constant speed motor at constant load

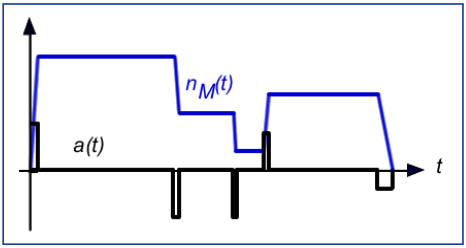


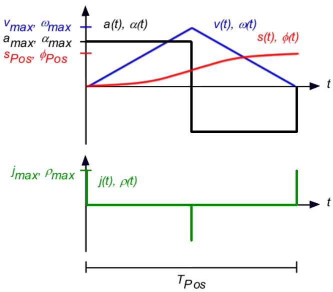
Figure 7 Speed profile of a variable speed motor

3.2.3 Motion laws for servo motors

For servo motors, the position is the leading value. The application requires a certain distance to move and specifies the permissible positioning time for this movement. Using a motion law, the velocity and the acceleration are derived from this.

The movement laws are defined for a positioning process. At the beginning and at the end of the movement the motor is at standstill.

Motion laws and parameters



The motion law used determines the specific mathematical relationship between position, velocity, acceleration and jerk.
All movement variables are interrelated and influence each other.

Table 11 Important parameters for motion laws

Parameters describing the positioning process	
T_{Pos}:	Positioning time, duration of the entire positioning process
s_{Pos}, φ_{Pos}:	Position setpoint, distance or angle to travel during the entire positioning process
v_{max}, ω_{max}:	Maximum velocity or angular speed during the entire positioning process
a_{max}, α_{max}:	Maximum acceleration or angular acceleration during the entire positioning process
j_{max}, ρ_{max}:	Maximum jerk or angular jerk during the entire positioning process

The following motion laws are considered.

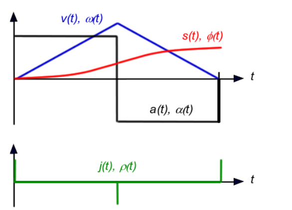
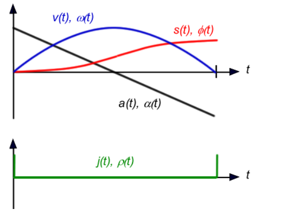
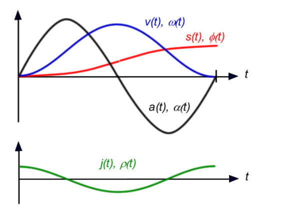
Time-optimised	Loss-optimised	Sine function
Allows the shortest positioning time with a maximum available torque.	Reduces losses during positioning to a minimum. The top velocity or speed achieved is lowest compared to other motion laws.	Protects the mechanics. The velocity or speed profile has no kinks, torque surges are avoided.
		

Table 12 Motion laws

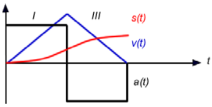
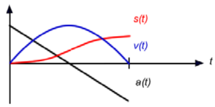
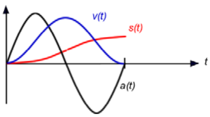
The following procedure is recommended for the definition of the motion laws' parameters at a given position setpoint:

1. Depending on the requirements of the application according to high dynamics, low losses and low stress on the mechanics the optimum motion law is selected.
2. Derivation of v_{max} respectively ω_{max} and a_{max} *respectively* α_{max} for the required position setpoint and positioning time.
3. Determination of the maximum speed and acceleration needed and comparison with the limit values v_P respectively ω_P and a_P respectively α_P permitted by the application
4. If the maximum permissible acceleration is exceeded, set $a_{max} = a_P$ respectively $\alpha_{max} = \alpha_P$ and determine T_{Pos}, v_{max} respectively ω_{max}.
5. If the maximum permissible speed is exceeded, set $a_{max} = a_P$, $v_{max} = v_P$ respectively $\alpha_{max} = \alpha_P$, $\omega_{max} = \omega_P$ and insert a constant speed phase with $v = v_{max}$ and determine T_{Pos}

The following diagrams show the mathematical relationships for the individual motion laws.

These motion laws are used in translatory movements if the desired position can be realized within the required positioning time without exceeding the permissible velocity and the permissible acceleration.

Translation, settings: s_{Pos}, T_{Pos}

Motion law	Parameter	Segment	Distance
 Time-optimised	$a_{max} = 4\frac{s_{Pos}}{T_{Pos}{}^2}$	I	$s = 2\frac{s_{Pos}}{T_{Pos}{}^2} \cdot t_I{}^2$
	$v_{max} = 2\frac{s_{Pos}}{T_{Pos}}$	III	$s = \frac{s_{Pos}}{2} + 2\frac{s_{Pos}}{T_{Pos}} \cdot t_{III} - 2\frac{s_{Pos}}{T_{Pos}{}^2} \cdot t_{III}{}^2$
 Loss-optimised	$a_{max} = 6\frac{s_{Pos}}{T_{Pos}{}^2}$		$s = 3\frac{s_{Pos}}{T_{Pos}{}^2} \cdot t^2 - 2\frac{s_{Pos}}{T_{Pos}{}^3} \cdot t^3$
	$v_{max} = \frac{3}{2}\frac{s_{Pos}}{T_{Pos}}$		
 Sine function	$a_{max} = 2\pi\frac{s_{Pos}}{T_{Pos}{}^2}$		$s = \frac{s_{Pos}}{T_{Pos}} \cdot \left[t - \frac{T_{Pos}}{2\pi} sin\left(\frac{2\pi}{T_{Pos}} t\right)\right]$
	$v_{max} = 2\frac{s_{Pos}}{T_{Pos}}$		

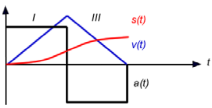
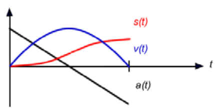
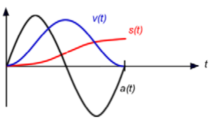
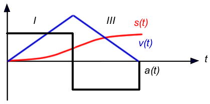
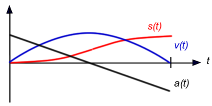
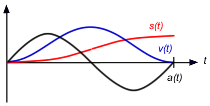
Motion law	Velocity	Acceleration
 Time-optimised	$v = 4\frac{s_{Pos}}{T_{Pos}{}^2} \cdot t_I$	$a = 4\frac{s_{Pos}}{T_{Pos}{}^2}$
	$v = 2\frac{s_{Pos}}{T_{Pos}} - 4\frac{s_{Pos}}{T_{Pos}{}^2} \cdot t_{III}$	$a = -4\frac{s_{Pos}}{T_{Pos}{}^2}$
 Loss-optimised	$v = 6\frac{s_{Pos}}{T_{Pos}{}^2} \cdot t - 6\frac{s_{Pos}}{T_{Pos}{}^3} \cdot t^2$	$a = 6\frac{s_{Pos}}{T_{Pos}{}^2} - 12\frac{s_{Pos}}{T_{Pos}{}^3} \cdot t$
 Sine function	$v = \frac{s_{Pos}}{T_{Pos}} \cdot \left[1 - cos\left(\frac{2\pi}{T_{Pos}} t\right)\right]$	$a = 2\pi\frac{s_{Pos}}{T_{Pos}{}^2} \cdot sin\left(\frac{2\pi}{T_{Pos}} t\right)$

Table 13 Motion laws of translation without limitations

These motion laws are used in translatory movements if the desired position leads to an exceeding of the permissible acceleration within the required positioning time. Then the positioning time is extended so that the maximum acceleration does not exceed the permissible acceleration.

Translation, settings: s_{Pos}, a_{max}

Motion law	Parameter	Segment	Distance
 Time-optimised	$T_I = T_{III} = \sqrt{\frac{s_{Pos}}{a_{max}}}$	I	$s = \frac{a_{max}}{2} \cdot t_I^{\,2}$
	$T_{Pos} = \sqrt{4\frac{s_{Pos}}{a_{max}}}$		
	$v_{max} = \sqrt{s_{Pos} \cdot a_{max}}$	III	$s = \frac{s_{Pos}}{2} + \sqrt{s_{Pos} \cdot a_{max}} \cdot t_{III} - \frac{a_{max}}{2} \cdot t_{III}^{\,2}$
 Loss-optimised	$T_{Pos} = \sqrt{6\frac{s_{Pos}}{a_{max}}}$		$s = \frac{a_{max}}{2} \cdot t^2 - \frac{1}{3} \cdot \frac{a_{max}}{T_{Pos}} \cdot t^3$
	$v_{max} = \sqrt{\frac{3}{8} s_{Pos} \cdot a_{max}}$		
 Sine function	$T_{Pos} = \sqrt{2\pi\frac{s_{Pos}}{a_{max}}}$		$s = a_{max}\frac{T_{Pos}}{2\pi} \cdot \left[t - \frac{T_{Pos}}{2\pi} sin\left(\frac{2\pi}{T_{Pos}} t\right)\right]$
	$v_{max} = \sqrt{\frac{2}{\pi} s_{Pos} \cdot a_{max}}$		

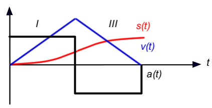
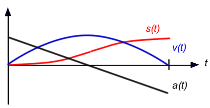
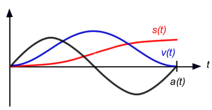
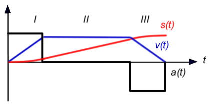
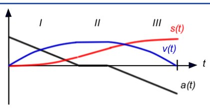
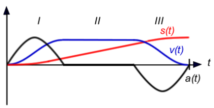
Motion law	Velocity	Acceleration
 Time-optimised	$v = a_{max} \cdot t_I$	$a = a_{max}$
	$v = \sqrt{s_{Pos} \cdot a_{max}} - a_{max} \cdot t_{III}$	$a = -a_{max}$
 Loss-optimised	$v = a_{max} \cdot t - \frac{a_{max}}{T_{Pos}} \cdot t^2$	$a = a_{max} - 2\frac{a_{max}}{T_{Pos}} \cdot t$
 Sine function	$v = a_{max}\frac{T_{Pos}}{2\pi} \cdot \left[1 - cos\left(\frac{2\pi}{T_{Pos}} t\right)\right]$	$a = a_{max} \cdot sin\left(\frac{2\pi}{T_{Pos}} t\right)$

Table 14 Motion laws of translation with limitation of acceleration

These motion laws are used in translatory movements if the desired position leads to an exceeding of the permissible acceleration and the permissible velocity within the required positioning time. A constant velocity segment is then inserted in the middle of the movement sequence and the positioning time is extended so that the acceleration does not exceed the permissible acceleration and the velocity does not exceed the permissible velocity.

Translation, settings s_{Pos}, a_{max}, v_{max}			
Motion law	**Parameter**	**Segment**	**Distance**
 Time-optimised	$T_I = T_{III} = \frac{v_{max}}{a_{max}}$	I	$s = \frac{a_{max}}{2}\cdot {t_I}^2$
	$T_{II} = \frac{s_{Pos}}{v_{max}} - \frac{v_{max}}{a_{max}}$	II	$s = \frac{{v_{max}}^2}{2\cdot a_{max}} + v_{max}\cdot t_{II}$
	$T_{Pos} = \frac{s_{Pos}}{v_{max}} + \frac{v_{max}}{a_{max}}$	III	$s = s_{Pos} - \frac{{v_{max}}^2}{2\cdot a_{max}} + v_{max}\cdot t_{III} - \frac{a_{max}}{2}\cdot {t_{III}}^2$
 Loss-optimised	If the motion sequence is determined by the maximum permissible velocity, the loss-optimised motion law has no advantage over the time-optimised motion law. In this case, the time-optimised motion law should be used.		
 Sine function	$T_I = T_{III} = \frac{\pi}{2}\frac{v_{max}}{a_{max}}$	I	$s = \frac{v_{max}}{2}\cdot\left[t_I - \frac{v_{max}}{2a_{max}}\sin\left(\frac{2a_{max}}{v_{max}}t_I\right)\right]$
	$T_{II} = \frac{s_{Pos}}{v_{max}} - \frac{\pi}{2}\frac{v_{max}}{a_{max}}$	II	$s = \frac{\pi}{4}\frac{{v_{max}}^2}{a_{max}} + v_{max}\cdot t_{II}$
	$T_{Pos} = \frac{s_{Pos}}{v_{max}} + \frac{\pi}{2}\frac{v_{max}}{a_{max}}$	III	$s = s_{Pos} - \frac{\pi}{4}\frac{{v_{max}}^2}{a_{max}} + \frac{v_{max}}{2}\cdot\left[t_{III} - \frac{v_{max}}{2a_{max}}\sin\left(\pi + \frac{2a_{max}}{v_{max}}t_{III}\right)\right]$

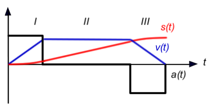
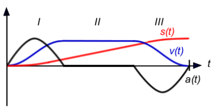
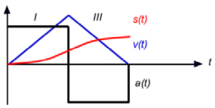
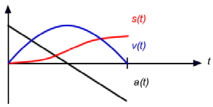
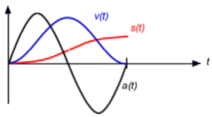
Motion law	**Velocity**	**Acceleration**
 Time-optimised	$v = a_{max}\cdot t_I$	$a = a_{max}$
	$v = v_{max}$	$a = 0$
	$v = v_{max} - a_{max}\cdot t_{III}$	$a = -a_{max}$
 Sine function	$v = \frac{v_{max}}{2}\cdot\left[1 - \cos\left(\frac{2a_{max}}{v_{max}}t_I\right)\right]$	$a = a_{max}\cdot\sin\left(\frac{2a_{max}}{v_{max}}t_I\right)$
	$v = v_{max}$	$a = 0$
	$v = \frac{v_{max}}{2}\cdot\left[1 - \cos\left(\pi + \frac{2a_{max}}{v_{max}}t_{III}\right)\right]$	$a = a_{max}\cdot\sin\left(\pi + \frac{2a_{max}}{v_{max}}t_{III}\right)$

Table 15 Motion laws of translation with limitation of acceleration and velocity

These motion laws are used in rotating movements if the desired position can be realized within the required positioning time without exceeding the permissible angular speed and the permissible angular acceleration.

Rotation, settings:: φ_{Pos}, T_{Pos}			
Motion law	**Parameter**	**Seg-ment**	**Distance**
 Time-optimised	$\alpha_{max} = 4\frac{\varphi_{Pos}}{T_{Pos}^{\ 2}}$	I	$\varphi = 2\frac{\varphi_{Pos}}{T_{Pos}^{\ 2}} \cdot t_I^{\ 2}$
	$\omega_{max} = 2\frac{\varphi_{Pos}}{T_{Pos}}$	III	$\varphi = \frac{\varphi_{Pos}}{2} + 2\frac{\varphi_{Pos}}{T_{Pos}} \cdot t_{III} - 2\frac{\varphi_{Pos}}{T_{Pos}^{\ 2}} \cdot t_{III}^{\ 2}$
 Loss-optimised	$\alpha_{max} = 6\frac{\varphi_{Pos}}{T_{Pos}^{\ 2}}$		$\varphi = 3\frac{\varphi_{Pos}}{T_{Pos}^{\ 2}} \cdot t^2 - 2\frac{\varphi_{Pos}}{T_{Pos}^{\ 3}} \cdot t^3$
	$\omega_{max} = \frac{3}{2}\frac{\varphi_{Pos}}{T_{Pos}}$		
 Sine function	$\alpha_{max} = 2\pi\frac{\varphi_{Pos}}{T_{Pos}^{\ 2}}$		$\varphi = \frac{\varphi_{Pos}}{T_{Pos}} \cdot \left[t - \frac{T_{Pos}}{2\pi} sin\left(\frac{2\pi}{T_{Pos}} t\right)\right]$
	$\omega_{max} = 2\frac{\varphi_{Pos}}{T_{Pos}}$		

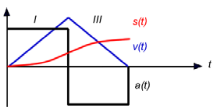
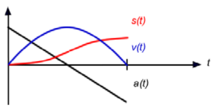
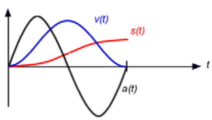
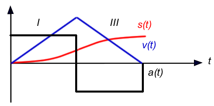
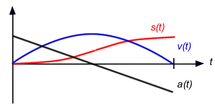
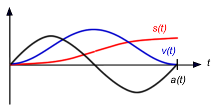
Motion law	**Velocity**	**Acceleration**
 Time-optimised	$\omega = 4\frac{\varphi_{Pos}}{T_{Pos}^{\ 2}} \cdot t_I$	$\alpha = 4\frac{\varphi_{Pos}}{T_{Pos}^{\ 2}}$
	$\omega = 2\frac{\varphi_{Pos}}{T_{Pos}} - 4\frac{\varphi_{Pos}}{T_{Pos}^{\ 2}} \cdot t_{III}$	$\alpha = -4\frac{\varphi_{Pos}}{T_{Pos}^{\ 2}}$
 Loss-optimised	$\omega = 6\frac{\varphi_{Pos}}{T_{Pos}^{\ 2}} \cdot t - 6\frac{\varphi_{Pos}}{T_{Pos}^{\ 3}} \cdot t^2$	$\alpha = 6\frac{\varphi_{Pos}}{T_{Pos}^{\ 2}} - 12\frac{\varphi_{Pos}}{T_{Pos}^{\ 3}} \cdot t$
 Sine function	$\omega = \frac{\varphi_{Pos}}{T_{Pos}} \cdot \left[1 - cos\left(\frac{2\pi}{T_{Pos}} t\right)\right]$	$\alpha = 2\pi\frac{\varphi_{Pos}}{T_{Pos}^{\ 2}} \cdot sin\left(\frac{2\pi}{T_{Pos}} t\right)$

Table 16 Motion laws of rotation without limitations

These motion laws are used in rotat movements if the desired position leads to an exceeding of the permissible angular acceleration within the required positioning time. Then the positioning time is extended so that the maximum angular acceleration does not exceed the permissible angular acceleration.

Rotation, settings: $\varphi_{Pos}, \alpha_{max}$

Motion law	Parameter	Segment	Angle
 Time-optimised	$T_I = T_{III} = \sqrt{\frac{\varphi_{Pos}}{\alpha_{max}}}$ $T_{Pos} = \sqrt{4\frac{\varphi_{Pos}}{\alpha_{max}}}$	I	$\varphi = \frac{\alpha_{max}}{2} \cdot {t_I}^2$
	$\omega_{max} = \sqrt{\varphi_{Pos} \cdot \alpha_{max}}$	III	$\varphi = \frac{\varphi_{Pos}}{2} + \sqrt{\varphi_{Pos} \cdot \alpha_{max}} \cdot t_{III} - \frac{\alpha_{max}}{2} \cdot {t_{III}}^2$
 Loss-optimised	$T_{Pos} = \sqrt{6\frac{\varphi_{Pos}}{\alpha_{max}}}$ $\omega_{max} = \sqrt{\frac{3}{8}\varphi_{Pos} \cdot \alpha_{max}}$		$\varphi = \frac{\alpha_{max}}{2} \cdot t^2 - \frac{1}{3} \cdot \frac{\alpha_{max}}{T_{Pos}} \cdot t^3$
 Sine function	$T_{Pos} = \sqrt{2\pi\frac{\varphi_{Pos}}{\alpha_{max}}}$ $\omega_{max} = \sqrt{\frac{2}{\pi}\varphi_{Pos} \cdot \alpha_{max}}$		$\varphi = \alpha_{max}\frac{T_{Pos}}{2\pi} \cdot \left[t - \frac{T_{Pos}}{2\pi} sin\left(\frac{2\pi}{T_{Pos}}t\right)\right]$

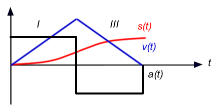
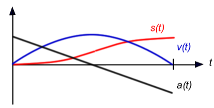
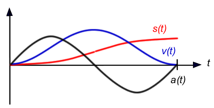
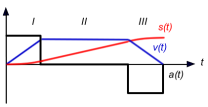
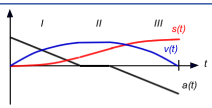
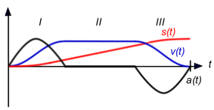
Motion law	Angular speed	Angular acceleration
 Time-optimised	$\omega = \alpha_{max} \cdot t_I$	$\alpha = \alpha_{max}$
	$\omega = \sqrt{\varphi_{Pos} \cdot \alpha_{max}} - \alpha_{max} \cdot t_{III}$	$\alpha = -\alpha_{max}$
 Loss-optimised	$\omega = \alpha_{max} \cdot t - \frac{\alpha_{max}}{T_{Pos}} \cdot t^2$	$\alpha = \alpha_{max} - 2\frac{\alpha_{max}}{T_{Pos}} \cdot t$
 Sine function	$\omega = \alpha_{max}\frac{T_{Pos}}{2\pi} \cdot \left[1 - cos\left(\frac{2\pi}{T_{Pos}}t\right)\right]$	$\alpha = \alpha_{max} \cdot sin\left(\frac{2\pi}{T_{Pos}}t\right)$

Table 17 Motion laws of rotation with limitation of angular acceleration

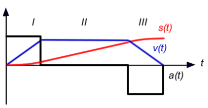
These motion laws are used in rotating movements if the desired position leads to an exceeding of the permissible angular acceleration and the permissible angular speed within the required positioning time. A constant angular speed segment is then inserted in the middle of the movement sequence and the positioning time is extended so that the angular acceleration does not exceed the permissible angular acceleration and the angular speed does not exceed the permissible angular speed.

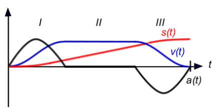
<table>
<tr><th colspan="4">Rotation, settings: $\varphi_{Pos}, \alpha_{Pos}, \omega_{max}$</th></tr>
<tr><th>Motion law</th><th>Parameter</th><th>Segment</th><th>Angle</th></tr>
<tr><td rowspan="3">

Time-optimised</td><td>$T_I = T_{III} = \frac{\omega_{max}}{\alpha_{max}}$</td><td>I</td><td>$\varphi = \frac{\alpha_{max}}{2} \cdot {t_I}^2$</td></tr>
<tr><td>$T_{II} = \frac{\varphi_{Pos}}{\omega_{max}} - \frac{\omega_{max}}{\alpha_{max}}$</td><td>II</td><td>$\varphi = \frac{{\omega_{max}}^2}{2 \cdot \alpha_{max}} + \omega_{max} \cdot t_{II}$</td></tr>
<tr><td>$T_{Pos} = \frac{\varphi_{Pos}}{\omega_{max}} + \frac{\omega_{max}}{\alpha_{max}}$</td><td>III</td><td>$\varphi = \varphi_{Pos} - \frac{{\omega_{max}}^2}{2 \cdot \alpha_{max}} + \omega_{max} \cdot t_{III} - \frac{\alpha_{max}}{2} \cdot {t_{III}}^2$</td></tr>
<tr><td>

Loss-optimised</td><td colspan="3">If the motion sequence is determined by the maximum permissible angular speed, the loss-optimised motion law has no advantage over the time-optimised motion law. In this case, the time-optimised motion law should be used.</td></tr>
<tr><td rowspan="3">

Sine function</td><td>$T_I = T_{III} = \frac{\pi}{2}\frac{\omega_{max}}{\alpha_{max}}$</td><td>I</td><td>$\varphi = \frac{\omega_{max}}{2} \cdot \left[t_I - \frac{\omega_{max}}{2\alpha_{max}} sin\left(\frac{2\alpha_{max}}{\omega_{max}} t_I\right)\right]$</td></tr>
<tr><td>$T_{II} = \frac{\varphi_{Pos}}{\omega_{max}} - \frac{\pi}{2}\frac{\omega_{max}}{\alpha_{max}}$</td><td>II</td><td>$\varphi = \frac{\pi}{4}\frac{{\omega_{max}}^2}{\alpha_{max}} + \omega_{max} \cdot t_{II}$</td></tr>
<tr><td>$T_{Pos} = \frac{\varphi_{Pos}}{\omega_{max}} + \frac{\pi}{2}\frac{\omega_{max}}{\alpha_{max}}$</td><td>III</td><td>$\varphi = \varphi_{Pos} + \frac{\omega_{max}}{2} \left[(T_I + t_{III}) - \frac{\omega_{max}}{2\alpha_{max}} sin\left(\frac{\pi(T_I + t_{III})}{T_I}\right)\right]$</td></tr>
</table>

<table>
<tr><th>Motion law</th><th>Angular speed</th><th>Angular acceleration</th></tr>
<tr><td rowspan="3">

Time-optimised</td><td>$\omega = \alpha_{max} \cdot t_I$</td><td>$\alpha = \alpha_{max}$</td></tr>
<tr><td>$\omega = \omega_{max} - \alpha_{max} \cdot t_{III}$</td><td>$\alpha = 0$</td></tr>
<tr><td>$\omega = \frac{\omega_{max}}{2} \cdot \left[1 - cos\left(\frac{2\alpha_{max}}{\omega_{max}} t_I\right)\right]$</td><td>$\alpha = -\alpha_{max}$</td></tr>
<tr><td rowspan="3">

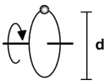
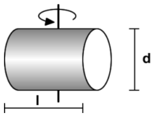
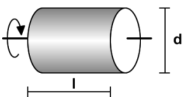
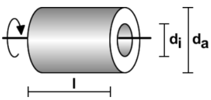
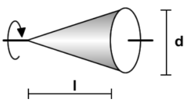
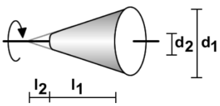
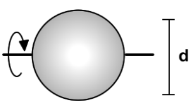
Sine function</td><td>$\omega = \frac{\omega_{max}}{2} \cdot \left[1 - cos\left(\frac{2\alpha_{max}}{\omega_{max}} t_I\right)\right]$</td><td>$\alpha = \alpha_{max} \cdot sin\left(\frac{2\alpha_{max}}{\omega_{max}} t_I\right)$</td></tr>
<tr><td>$\omega = \omega_{max}$</td><td>$\alpha = 0$</td></tr>
<tr><td>$\omega = \frac{\omega_{max}}{2} \cdot \left[1 - cos\left(\frac{\pi(T_I + t_{III})}{T_I}\right)\right]$</td><td>$\alpha = \alpha_{max} \cdot sin\left(\frac{\pi(T_I + t_{III})}{T_I}\right)$</td></tr>
</table>

Table 18 Motion laws of rotating with limitation of angular acceleration and angular speed

3.3 Masses and moments of inertia

Electrical motors move mechanical elements. Their masses and moments of inertia determine the motor torque required for the movement.

The masses and moments of inertia of the mechanical elements are determined by the material used and by their geometrical form. In case of rotational movements, the position of the rotational axis additionally has an influence on the moment of inertia.
The masses and moments of inertia of the most important geometric basic bodies are given below. In the determination of the moment of inertia, it is assumed that the rotational axis runs through the gravitational centre of the basic body.

Body	Graphical representation	Mass m	Moment of inertia J
Point mass		m_P	$J = \frac{1}{4} m_P \cdot d^2$
Cylinder		$m = \frac{\pi}{4} \rho \cdot l \cdot d^2$	$J_S = \frac{\pi}{64} \rho \cdot l \cdot d^4 + \frac{\pi}{48} \rho \cdot l^3 \cdot d^2$
Cylinder		$m = \frac{\pi}{4} \rho \cdot l \cdot d^2$	$J_S = \frac{\pi}{32} \rho \cdot l \cdot d^4$
Hollow-cylinder		$m = \frac{\pi}{4} \rho \cdot l \cdot [{d_a}^2 - {d_i}^2]$	$J_S = \frac{\pi}{32} \rho \cdot l \cdot [{d_a}^4 - {d_i}^4]$
Cone		$m = \frac{\pi}{12} \rho \cdot l \cdot d^2$	$J_S = \frac{\pi}{160} \rho \cdot l \cdot d^4$
Truncated cone		$m = \frac{\pi}{12} \rho \cdot [(l_1 + l_2){d_1}^2 - l_2 {d_2}^2]$	$J_S = \frac{\pi}{160} \rho \cdot [(l_1 + l_2){d_1}^4 - l_2 {d_2}^4]$
Sphere		$m = \frac{\pi}{6} \rho \cdot d^3$	$J_S = \frac{\pi}{60} \rho \cdot d^5$

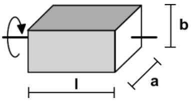
Cuboid		$m = \rho \cdot l \cdot a \cdot b$	$J_S = \frac{1}{12}\rho \cdot l \cdot ab[a^2 + b^2]$
J_S: Moment of inertia, in which the axis of rotation passes through the centre of gravity		m: Mass ρ: Density l Length	d: Diameter a: Width b: Height

Table 19 Mass and moment of inertia of geometric basic bodies

Real mechanical elements are often realised by a combination of geometrical basic bodies. In this case, the mechanical element is decomposed into its basic bodies and the mass and the moment of inertia of the mechanical element are calculated in 3 steps:

1. **Determination of the masses and moments of inertia of all basic bodies**
   It should be noted that the rotational axis, which is set during the determination of the moments of inertia of the basic body, is parallel to the actual rotational axis of the mechanical element.
2. **Application of Steiner's theorem**
   Application of Steiner's theorem For all the basic bodies whose rotational axis in the first calculation step has a parallel offset to the rotational axis of the mechanical element, the moment of inertia is determined with reference to the actual rotational axis of the mechanical element.
3. **Addition of all masses and moments of inertia**
   The masses and moments of inertia of the basic bodies determined in the first and second steps are added and give the mass and the moment of inertia of the mechanical element.

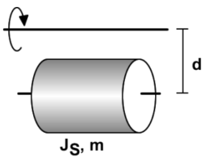
Steiner's theorem	Moment of inertia J
	$J = J_S + m \cdot d^2$
J: Moment of inertia m: Mass	d: Distance of rotational axes J_S: Moment of inertia, in which the rotational axis passes through the centre of gravity

Table 20 Steiner's theorem

In order to determine the masses and moments of inertia, the density of the material the geometric basic bodies consist of must be known. For some frequently used construction materials, the values for their density are given below.

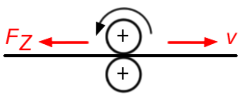
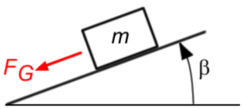
Material	Density ρ
Acrylic	1190 kg/m³
Aluminium	2700 kg/m³
Bronze	8100 kg/m³
Oak wood	670 kg/m³
Spruce	470 kg/m³
Glass	2500 kg/m³
Cast iron	7600 kg/m³
Rubber	950 kg/m³
Laminated paper	1400 kg/m³
Copper	8940 kg/m³
Brass	8500 kg/m³
Polyethylene	930 kg/m³
Polyvinylchloride	1300 kg/m³
Steel	7900 kg/m³

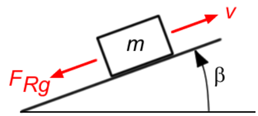
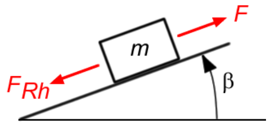
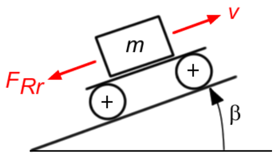
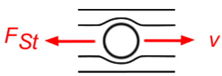
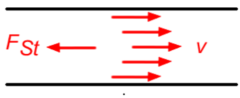
Table 21 Density of frequently used construction materials

3.4 Load forces and load torques

In the mechanical system work is performed. This leads to load forces, which have be applied by the electrical motor as motor torque.

If the load force acts on the surface of rotating mechanical elements, the effective load torque can be determined according to Figure 5.

Name	Graphical representation	Load force
Traction force		F_Z
Weight force, downhill slope force		$F_G = m \cdot g \cdot \sin(\beta)$

Sliding friction		$= \mu_G \cdot m \cdot g \cdot \cos(\beta)$ For v≠ 0, F_{Rg} acts against the actual velocity.
Static friction		$_{R\ h} = \mu_H \cdot m \cdot g \cdot \cos(\beta)$ For v= 0, F_{Rh} acts against the actual force F.
Rolling friction		$= c_R \cdot m \cdot g \cdot \cos(\beta)$ For v≠ 0, F_{Rr} acts against the actual velocity.
Flow resistance		$F_{St} = c_W \cdot A \frac{\rho \cdot v^2}{2}$ For v≠ 0, F_{St} acts against the actual velocity.
Flow resistance for a laminar flow in a tube		$F_{St} = 8\pi \cdot \eta l \cdot v$ For v≠ 0, F_{St} acts against the actual velocity.

F:	Load force	l:	Length of the tube
m:	Mass to be moved	v:	Velocity
g:	Acceleration due to gravity	η:	Viscosity of the flowing medium
β:	Angle of inclination	ρ:	Density of the medium
μ_G:	Sliding friction coefficient	c_W:	Drag coefficient
μ_H:	Static friction coefficient	A:	Reference area (e.g. face of a vehicle, inner surface of a tube)
c_R:	Rolling friction coefficient		

Table 22 Typical load forces

The following table shows some typical values of friction coefficients. These should be checked and adjusted according to the real application.

	Sliding friction coefficients μG	**Static friction coefficients μH**	**Rolling friction coefficients cR**
Steel on steel without lubrication	0,12	0,15	0,0005 - 0,0010 (Ball bearing)
Steel on steel with lubrication	0,01	0,01	0,001 - 0,002 (Railway wheel on rail)

Steel on Bronze without lubrication	0,18	0,19	0,01 - 0,02 (Tires on asphalt or concrete)
Steel on Bronze with lubrication	0,07		

Table 23 Typical values of friction coefficients

The load force that emanates from flowing media is determined by its viscosity. In real applications, this must be determined as a function of the temperature.

Material	**Temperature υ**	**Viscosity η**
Water	20°C	$1\,mPa \cdot s = 0{,}0001\,\frac{N}{m^2}s$
Motor oil	150°C	$3\,mPa \cdot s = 0{,}0003\,\frac{N}{m^2}s$
Motor oil	25°C	$100\,mPa \cdot s = 0{,}01\,\frac{N}{m^2}s$

Table 24 Typical values of viscosity

3.5 Example: Pump motor

The pump motor of the heating system runs 18 hours each day and is switched off during the night for the purpose of energy saving for 6 hours. The speed of the pump should be approx. 3000 rpm. This results in the following motion sequence for the pump motor.

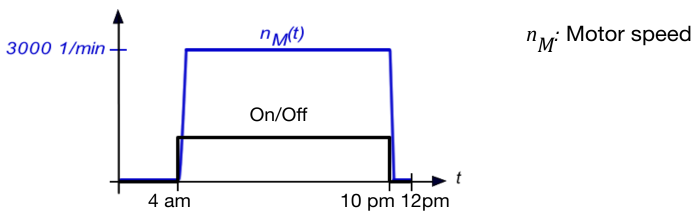
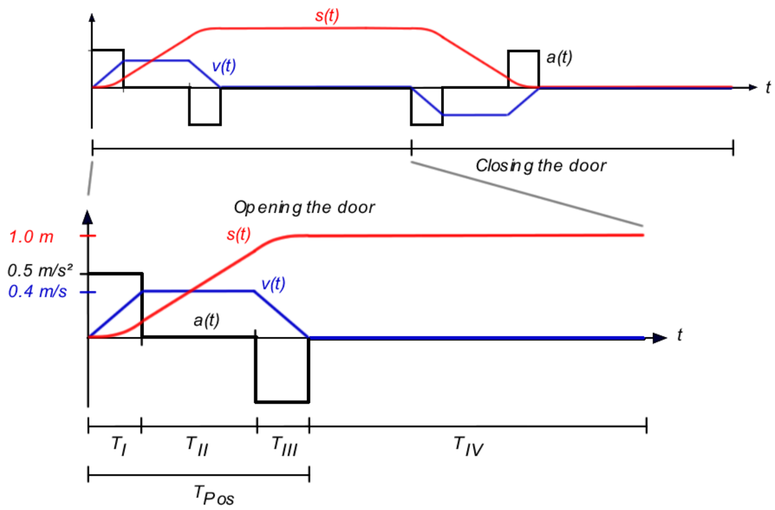


Table 25 Motion sequence of a pump motor

3.6 Example: Door motor

For the motion sequence of the door motor the following parameters are given:
Travel distance (width of the door) S_{Pos}:: 1.0 m, Maximum acceleration a_{max}: 0.5 m / s², Maximum velocity V_{max}: 0.4 m / s, Minimum pause between two positioning sequences T_{IV} 5 s

The movements for opening and closing the door are time-optimised using the same motion parameters. Therefore, it is sufficient to treat the operation for opening the door only. The mathematical equations according to Table 15 are used. This results in the following motion sequence of the door motor.



T_I, T_{III}: Duration of the acceleration and deceleration phases	$T_I = T_{III} = \frac{v_{max}}{a_{max}} = \frac{0{,}4\ m \cdot s^2}{s \cdot 0{,}5\ m} = 0{,}8\ s$
T_{II}: Duration of the constant speed phase	$T_{II} = \frac{s_{Pos}}{v_{max}} - \frac{v_{max}}{a_{max}} = \frac{1\ m \cdot s}{0{,}4\ m} - \frac{0{,}4\ m \cdot s^2}{s \cdot 0{,}5\ m} = 1{,}7\ s$
T_{Pos}: Positioning time, duration of the entire positioning sequence	$T_{Pos} = \frac{s_{Pos}}{v_{max}} + \frac{v_{max}}{a_{max}} = \frac{1\ m \cdot s}{0{,}4\ m} + \frac{0{,}4\ m \cdot s^2}{s \cdot 0{,}5\ m} = 3{,}3\ s$
T_{IV}: Duration of pause	$T_{IV} = 5{,}0\ s$
s: Travel distance v: Velocity	a: Acceleration

Table 26 Motion sequence of a door motor

4 Motion conversion with gears

Gearboxes are mechanical converters. They convert the speed and the torque of the motor in such a way that they meet the requirements of the application. This process includes the conversion of the motion type from a rotational motor movement into a translatory movement of the load.

If the load performs a linear movement, the motor train including the load is referred to as a linear axis. If the movement of the load is rotational, the motor train including the load is referred to as a rotating axis.

Often, application-specific mechanical converters are included in the machines. They are treated mathematically as gears. Each gearbox has a driving side and a driven side. There are mathematical relationships between the physical values of the driving and driven side. In case of constant transmission gears, these relationships are linear. In case of variable transmission gears they are not linear.

In many applications, several gears are arranged one behind the other. The first gear often converts the motion type from translational to rotational and a downstream rotational gearbox adjusts the speed, the torque as well as the geometrical direction of the axes.

Mechanical friction occurs in gears. Part of the energy fed into the gearbox is converted into heat and thus lost. If the energy flows from the motor to the working machine, the motor must cover the losses in the gear. If the energy flows from the working machine to the motor (e.g. during braking), the working machine covers the losses in the gear. Therefore different equations for the calculation

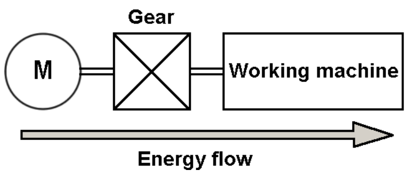
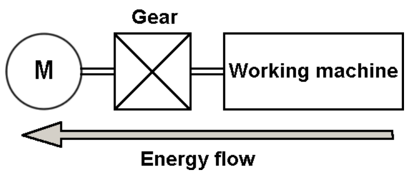
Motor operation	**Generator operation**
	
Boundary conditions: $F > 0, v > 0$ or $F < 0, v < 0t$ or $M > 0, \omega > 0$ or $M < 0, \omega < 0$	Boundary conditions: $F > 0, v < 0$ or $F < 0, v > 0$ or $M > 0, \omega < 0$ or $M < 0, \omega > 0$
F: Force v: Velocity	M: Torque ω: Angular speed

Table 27 Energy flow at motor and generator operation

4.1 Rotating axes

4.1.1 Rotating load

A rotating load occurs if forces are applied to the surface of a rotating roller or a rotating work piece. Rotating tables are also among the rotating loads.

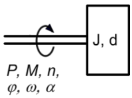
Rotating load	Equations	
	n: Speed driving side (1/s)	$n = \frac{\omega}{2\pi}$
	M: Torque driving side	$M = J\frac{d\omega}{dt} + F_L\frac{d}{2}$
	P: Power driving side	$P = M\omega$
φ: Angle driving side and driven side ω: Angular speed driving side and driven side α: Angular acceleration driving side and driven side J: Moment of inertia load d: Diameter load		

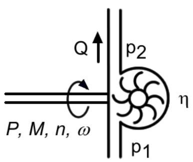
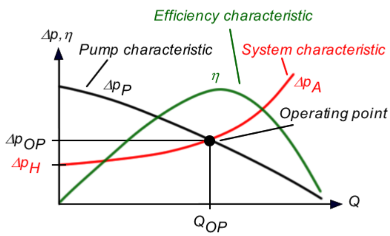
Table 28 Equations of the rotating load

4.1.2 Pump

A pump is defined by an experimentally determined pump characteristic ΔpP(Q). This characteristic is valid at a fixed speed of the pump as well as at a defined temperature and a defined conveying medium.

Plants which are supplied with the volume flow produced by the pump have a system characteristic Δ_{pA}(Q). In general, the system characteristic has the shape of a parabola, which has been shifted upwards from the coordinate origin. The operating point of the pump is located where the pump characteristic intersects the system characteristic. At this operating point, the volume flow is determined.

In addition to the pump characteristic, pumps also have an efficiency characteristic η(Q). If the volume flow is known at the operating point, the required input power at the shaft of the pump can be determined.

Pump	Equations
	

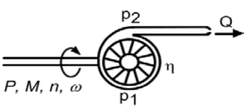
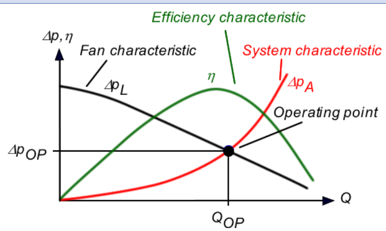
Δp_A: Pressure difference of the plant (system characteristic) for n = constant	$\Delta p_A = f(Q)$
Δp_P: Pressure difference of the pump (pump characteristic) for n = constant	$\Delta p_P = p_2 - p_1 = f(Q)$
H: Discharge head of the pump (pump characteristic) for n = constant	$H = \frac{\Delta p_P}{\rho \cdot g} = f(Q)$
η: Efficiency characteristic of the pump for n = constant	$\eta = f(Q)$
n: Speed driving side (1/s)	n= constant
P_P: Conveying capacity of the pump	$P_P = \Delta p_P \cdot Q_P$
P: Power driving side	$P = \frac{\Delta p_{AP} \cdot Q_{AP}}{\eta}$
M: Torque driving side	$M = \frac{P}{2\pi \cdot n}$
p_1: Pressure at the inlet of the pump p_2: Pressure at the outlet of the pump Δp_{AP}: Pressure difference at operating point ρ: Density of medium to be pumped	g: Acceleration due to gravity Q: Volume flow of the medium to be pumped Q_{AP}: Volume flow of the medium to be pumped at operating point

Table 29 Equations of the pump

4.1.3 Fan

A fan is defined by an experimentally determined fan characteristic Δ_{pL}(Q). This characteristic is determined at a fixed speed of the fan as well as at a defined temperature and air density. Plants which are supplied with the volume flow produced by the fan have a system characteristic Δ_{pA}(Q). In general, the system characteristic has the shape of a parabola starting at the coordinate origin.

The operating point of the fan is located where the fan characteristic intersects the system characteristic. At this operating point, the volume flow is determined. In addition to the fan characteristic, fans also have an efficiency characteristic η(Q). If the volume flow is known at the operating point, the required input power at the shaft of the fan can be determined.

Fan	Equations
	

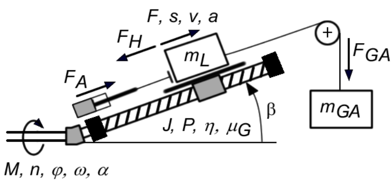
Δp Δp_A: Pressure difference of the plant (system characteristic) for n = constant	$\Delta p_A = f(Q)$
Δp_L: Pressure difference of the fan (fan characteristic) for n = constant	$\Delta p_L = p_2 - p_1 = f(Q)$
η: Efficiency characteristic of the fan for n = constant	$\eta = f(Q)$
n: Speed driving side (1/s)	n= constant
P: Power driving side	$P = \frac{\Delta p_{AP} \cdot Q_{AP}}{\eta}$
M: Torque driving side	$M = \frac{P}{2\pi \cdot n}$
p_1: Air pressure at the inlet of the fan p_2: Air pressure at the outlet of the fan	Q: Volume flow of the air Q_{OP}: Volume flow of the medium to be pumped at operating point

Table 30 Equations of the fan

4.2 Linear axes

4.2.1 Spindle

A spindle realises linear movement of the load in a limited travel range. The load is fixed so that vertical motion is also possible. The required torque at the driving side can be reduced by means of load and force compensation.

<table>
<tr><th>Spindle</th><th colspan="2">Equations</th></tr>
<tr><td rowspan="6">

Boundary condition: $0 \le \beta \le \frac{\pi}{2}$</td><td>$\varphi$: Angle driving side</td><td>$\varphi = s \cdot \frac{2\pi}{P}$</td></tr>
<tr><td>ω: Angular speed driving side</td><td>$\omega = v \cdot \frac{2\pi}{P}$</td></tr>
<tr><td>n: Speed driving side (1/s)</td><td>$n = v \cdot \frac{1}{P}$</td></tr>
<tr><td>α: Angular acceleration driving side</td><td>$\alpha = a \cdot \frac{2\pi}{P}$</td></tr>
<tr><td>M: Torque driving side, motor operation</td><td>$M = J \cdot \alpha + \left[F \cdot \frac{P}{2\pi}\right] \cdot \frac{1}{\eta}$</td></tr>
<tr><td>M: Torque driving side, generator operation</td><td>$M = J \cdot \alpha + \left[F \cdot \frac{P}{2\pi}\right] \cdot \eta$</td></tr>
<tr><td colspan="2">F: Linear force</td><td>$F = F_H + F_B + F_R - F_A - F_{GA}$</td></tr>
<tr><td colspan="2">F_H: Downhill slope force of the load, the slide and the nut</td><td>$F_H = m_L \cdot g \cdot sin(\beta)$</td></tr>
<tr><td colspan="2">F_B: Acceleration force of the load, the slide and the nut</td><td>$F_B = m \cdot a$</td></tr>
<tr><td rowspan="3">F_R: Friction force in the guidance of the slide</td><td>$v>0$</td><td>$F_R = \mu_G \cdot m_L \cdot g \cdot cos(\beta)$</td></tr>
<tr><td>$v=0$</td><td>$F_R = 0$</td></tr>
<tr><td>$v<0$</td><td>$F_R = -\mu_G \cdot m_L \cdot g \cdot cos(\beta)$</td></tr>
</table>

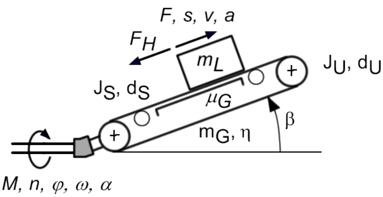
F_A: Force of the force compensation (Is determined by the application.)	$F_A = f(t)$
F_{GA}: Force of the weight compensation (Applicable, if dv/dt < g.)	$F_{GA} = m_{GA}[g - a]$
s: Distance driven side v: Velocity driven side a: Acceleration driven side P: Pitch of the spindle η: Efficiency of the spindle J: Moment of inertia of the spindle	β: Incline of the spindle related to the horizontal μ_G: Sliding friction coefficient m_L: Mass of the load, the slide and the nut m_{GA}: Mass of the counterweight g: Acceleration due to gravity

Table 31 Equations of the spindle

4.2.2 Conveyor belt

A conveyor belt realises linear movement of the load in a theoretically infinite travel range.

The load is often fixed only by static friction so that the slope of the conveyor belt is limited.

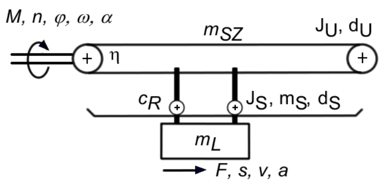
Conveyor belt		**Equations**	
 Boundary condition: $0 \leq \beta \leq \frac{\pi}{2}$		φ: Angle driving side	$\varphi = s \cdot \frac{2}{d_U}$
		ω: Angular speed driving side	$\omega = v \cdot \frac{2}{d_U}$
		n: Speed driving side (1/s)	$n = v \cdot \frac{1}{\pi d_U}$
		α: Angular acceleration driving side	$\alpha = a \cdot \frac{2}{d_U}$
		M: Torque driving side, motor operation	$M = 2 \cdot J_U \cdot \alpha + \left[F \cdot \frac{d_U}{2}\right] \cdot \frac{1}{\eta}$
		M: Torque driving side, generator operation	$M = 2 \cdot J_U \cdot \alpha + \left[F \cdot \frac{d_U}{2}\right] \cdot \eta$
F: Linear Force		$F = F_H + F_B + F_R$	
F_H: Downhill slope force of the load		$F_H = m_L \cdot g \cdot sin(\beta)$	
F_B: Acceleration force of the load, the belt and the support rolls		$F_B = \left[m_L + m_G + n_S J_S \frac{4}{{d_S}^2}\right] \cdot a$	
F_R: Friction force of the load	$v>0$	$F_R = \mu_G \cdot m_L \cdot g \cdot cos(\beta)$	
	$v=0$	$F_R = 0$	
	$v<0$	$F_R = -\mu_G \cdot m_L \cdot g \cdot cos(\beta)$	

s:	Distance driven side	η:	Efficiency of the conveyor belt
v:	Velocity driven side	β:	Incline of the conveyor belt related to the horizontal
a:	Acceleration driven side	μ_G:	Sliding friction coefficient
d_U:	Diameter of the pulleys	m_L:	Mass of the load
d_S:	Diameter of the support rolls	m_G:	Mass of the belt
n_S:	Number of the support rolls	g:	Acceleration due to gravity
J_U:	Moment of inertia of a pulley		
J_S:	Moment of inertia of a support roll		

Table 32 Equations of the conveyor belt

4.2.3 Wire rope and belt

The wire rope or belt realises horizontal movements of a load in a limited travel range.

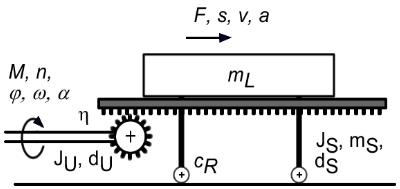
Wire rope, belt		Equations		
		φ:	Angle driving side	$\varphi = s \cdot \frac{2}{d_U}$
		ω:	Angular speed driving side	$\omega = v \cdot \frac{2}{d_U}$
		n:	Speed driving side (1/s)	$n = v \cdot \frac{1}{\pi d_U}$
		α:	Angular acceleration driving side	$\alpha = a \cdot \frac{2}{d_U}$
		M:	Torque driving side, motor operation	$M = 2 \cdot J_U \cdot \alpha + \left[F \cdot \frac{d_U}{2}\right] \cdot \frac{1}{\eta}$
		M:	Torque driving side, generator operation	$M = 2 \cdot J_U \cdot \alpha + \left[F \cdot \frac{d_U}{2}\right] \cdot \eta$
F: Linear Force		$F = F_B + F_R$		
F_B: Acceleration force of the load, the rope or the belt and the support rolls		$F_B = \left[m_L + m_{SZ} + n_S m_S + n_S J_S \frac{4}{{d_S}^2}\right] \cdot a$		
F_R: Friction force of the load	$v>0$	$F_R = c_R \cdot [m_L + n_S m_S] \cdot g$		
	$v=0$	$F_R = 0$		
	$v<0$	$F_R = -c_R \cdot [m_L + n_S m_S] \cdot g$		

s:	Distance driven side	η:	Efficiency of the wire rope or belt
v:	Velocity driven side	c_R:	Rolling friction coefficient
a:	Acceleration driven side	m_L:	Mass of the load
d_U:	Diameter of the pulleys	m_S:	Mass of a support roll
d_S:	Diameter of the support rolls	m_{SZ}:	Mass of the rope or the belt
n_S:	Number of the support rolls	g:	Acceleration due to gravity
J_U:	Moment of inertia of a pulley		
J_S:	Moment of inertia of a support roll		

Table 33 Equations of the wire rope or belt

4.2.4 Toothed rack

A toothed rack realises horizontal movements of a load in a limited travel range.



Toothed Rack	Equations	
(figure above)	φ: Angle driving side	$\varphi = s \cdot \frac{2}{d_U}$
	ω: Angular speed driving side	$\omega = v \cdot \frac{2}{d_U}$
	n: Speed driving side (1/s)	$n = v \cdot \frac{1}{\pi d_U}$
	α: Angular acceleration driving side	$\alpha = a \cdot \frac{2}{d_U}$
	M: Torque driving side, motor operation	$M = J_U \cdot \alpha + \left[F \cdot \frac{d_U}{2}\right] \cdot \frac{1}{\eta}$
	M: Torque driving side, generator operation	$M = J_U \cdot \alpha + \left[F \cdot \frac{d_U}{2}\right] \cdot \eta$

F: Linear Force		$F = F_B + F_R$
F_B: Acceleration force of the load, the toothed rack and the support rolls		$F_B = \left[m_L + n_S m_S + n_S J_S \frac{4}{{d_S}^2}\right] \cdot a$
F_R: Friction force of the load	$v>0$	$F_R = c_R \cdot [m_L + n_S m_S] \cdot g$
	$v=0$	$F_R = 0$
	$v<0$	$F_R = -c_R \cdot [m_L + n_S m_S] \cdot g$

s:	Distance driven side	J_S:	Moment of inertia of a support roll
v:	Velocity driven side	η:	Efficiency of the toothed rack
a:	Acceleration driven side	c_R:	Rolling friction coefficient
d_U:	Diameter of the driving pinion	m_L:	Mass of the load and the toothed rack
d_S:	Diameter of the support rolls	m_S:	Mass of a support roll
n_S:	Number of the support rolls	g:	Acceleration due to gravity

Table 34 Equations of the toothed rack

4.2.5 Hoist

The hoist realises vertical movements of the load in a limited travel range. The torque needed at the driving side of the rope drum can be reduced by a combination of movable and fixed deflection pulleys.

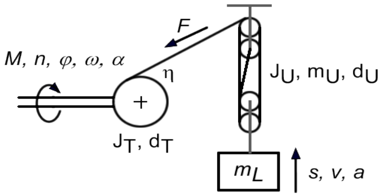
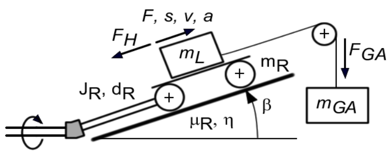
Running gear	Equations	
	*z:* Number of supporting ropes	$z = n_F + n_L$
	φ: Angle driving side	$\varphi = s \cdot \frac{2z}{d_T}$
	ω: Angular speed driving side	$\omega = v \cdot \frac{2z}{d_T}$
	n: Speed driving side (1/s)	$n = v \cdot \frac{z}{\pi d_T}$
Boundary condition: • $n_F \geq 1;\ n_F - 1 \leq n_L$ • The mass of the rope and the hook can be neglected.	*α:* Angular acceleration driving side	$\alpha = a \cdot \frac{2z}{d_T}$
	M: Torque driving side, motor operation	$M = J_T \cdot \alpha + \left[F \cdot \frac{d_T}{2}\right] \cdot \frac{1}{\eta}$
	M: Torque driving side, generator operation	$M = J_T \cdot \alpha + \left[F \cdot \frac{d_T}{2}\right] \cdot \eta$
F: Linear Force at the rope drum	$F = F_G + F_B$	
F_G: Weight force of the load at the rope drum	$F_G = \frac{1}{z}[m_L + n_L m_U] \cdot g$	
F_B: Acceleration force of the load and the pulleys at the rope drum	$F_B = \left[\frac{1}{z}(m_L + n_L m_U) + J_U \frac{4z(z-1)}{{d_U}^2}\right] \cdot a$	
s: Distance driven side *v:* Velocity driven side *a:* Acceleration driven side *d_U:* Diameter of the pulleys *d_T:* Diameter of the rope drum *n_L:* Number of movable deflection pulleys *n_F:* Number of fixed deflection pulleys, contains rope drum and fixed rolls	*J_U:* Moment of inertia of a pulley *J_T:* Moment of inertia of the rope drum *η:* Efficiency of the rope drum *m_L:* Mass of the load *m_U:* Mass of a deflection pulley *g:* Acceleration due to gravity	

Table 35 Equations of the hoist

4.2.6 Running gear

A running gearbox realises linear movements of the load in a theoretically infinite travel range. The transmission of force is done by the friction of the driven wheels on the ground. Therefore, the slope of the ground is limited.

Running gear	Equations	
	*φ:* Angle driving side	$\varphi = s \cdot \frac{2}{d_R}$
	ω: Angular speed driving side	$\omega = v \cdot \frac{2}{d_R}$
	n: Speed driving side	$n = v \cdot \frac{1}{\pi d_R}$
Boundary condition: $0 \leq \beta \lesssim^{\pi}$	*α:* Angular acceleration driving side	$\alpha = a \cdot \frac{2}{d_R}$

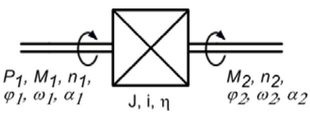
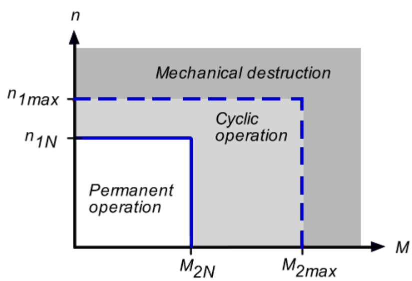
Boundary condition: $0 \leq \beta \leq \frac{\pi}{2}$		*M:* Torque driving side, motor operation	$M = n_R \cdot J_R \cdot \alpha + \left[F \cdot \frac{d_R}{2}\right] \cdot \frac{1}{\eta}$
		M: Torque driving side, generator operation	$M = n_R \cdot J_R \cdot \alpha + \left[F \cdot \frac{d_R}{2}\right] \cdot \eta$
F:	Linear Force		$F = F_H + F_B + F_R - F_{GA}$
F_H:	Downhill slope force of the load, the running gear and the wheels		$F_H = [m_L + n_R m_R] \cdot g \cdot sin(\beta)$
F_B:	Acceleration force of the load, the running gear and the wheels		$F_B = [m_L + n_R m_R] \cdot a$
F_R:	Friction force of the load	*v>0*	$F_R = c_R \cdot [m_L + n_R m_R] \cdot g \cdot cos(\beta)$
		v=0	$F_R = 0$
		v<0	$F_R = -c_R \cdot [m_L + n_R m_R] \cdot g \cdot cos(\beta)$
F_{GA}:	Force of the weight compensation (Applicable, if dv/dt < g.)		$F_{GA} = m_{GA} \cdot [g - a]$
s: *v:* *a:* d_R: n_R:	Distance driven side Velocity driven side Acceleration driven side Diameter of the wheels Number of the wheels	J_R: c_R: m_L: m_{GA}: m_R: *g:*	Moment of inertia of a wheel Rolling friction coefficient Mass of the load and the running gear Mass of the counterweight Mass of a wheel Acceleration due to gravity

Table 36 Equations of the running gear

4.3 Rotating gear

4.3.1 Mathematical description and parameters

Rotating gears are used to adjust rotational motion variables and the shaft alignment between the motor and the working machine.

Rotating gear		**Equations**
		
φ_1:	Angle driving side	$\varphi_1 = \varphi_2 \cdot i$
ω_1:	Angular speed driving side	$\omega_1 = \omega_2 \cdot i$

n_1:	Speed driving side	$n_1 = n_2 \cdot i$
α:	Angular acceleration driving side	$\alpha_1 = \alpha_2 \cdot i$
M_1:	Torque driving side, motor operation	$M_1 = J \cdot \alpha_1 + \frac{M_2}{i} \cdot \frac{1}{\eta}$
M_1:	Torque driving side, generator operation	$M_1 = J \cdot \alpha_1 + \frac{M_2}{i} \cdot \eta$
P_1:	Power driving side	$P_1 = M_1 \omega_1$
n_{1N}:	Rated speed at driving side	The speed, the gearbox can provide at its driving side permanently.
n_{1max}:	Maximum permissible speed at driving side	The maximum speed, the gearbox can provide at its driven side without mechanical destruction.
M_{2N}:	Rated torque at driven side	The torque, the gearbox can provide permanently without additional cooling measures at its driven side. The rated torque is also referred to as the permanent torque.
M_{2max}:	Maximum permissible torque at driven side	The maximum torque, the gearbox can provide at its driven side without mechanical destruction.
n_2: φ_2: ω_2: α_2:	Speed driven side Angle driven side Angular speed driven side Angular acceleration driven side	M_2: Torque driven side i: Gear ratio J: Moment of inertia of the gearbox related to driving side

Table 37 Equations of the rotating gearbox

To determine the motion sequences on the output side of the gearbox you have to select it from the catalogue. The selection is made taking into account the mechanical and thermal properties of the gear, which are represented by characteristic curves.

4.3.2 Selection of the optimum gear ratio

The gear ratio has to be selected in a way that the maximum occurring speed at the driven side of the gearbox is translated into a speed which is covered by the motor type selected according to chapter 1.

This results in a permissible range of gear ratio, which can be used for the optimization of the motor train.

- For constant and variable speed motors, a small gear ratio should be selected. A small gear ratio often results in a high efficiency of the gearbox and reduces the losses of the motor train.
- For servo motors, the gear ratio should be as close as possible to the optimum value i_{opt} .

$i_{opt} = \sqrt{\frac{J_2}{J_1}}$	i_{opt}:	Optimum gear ratio
	J_1:	Sum of the moments of inertia at the driving side
	J_2	Sum of the moments of inertia at the driven side

Table 38 Optimum gear ratio for servo motors

In this case, the motor torque needed for the realization of the motion sequence is the lowest. A selection of the gear ratio close to the optimum leads to a smaller motor and a smaller control unit.

4.3.3 Selection of the optimum gearbox type

Rotating gearboxes are offered in various types.

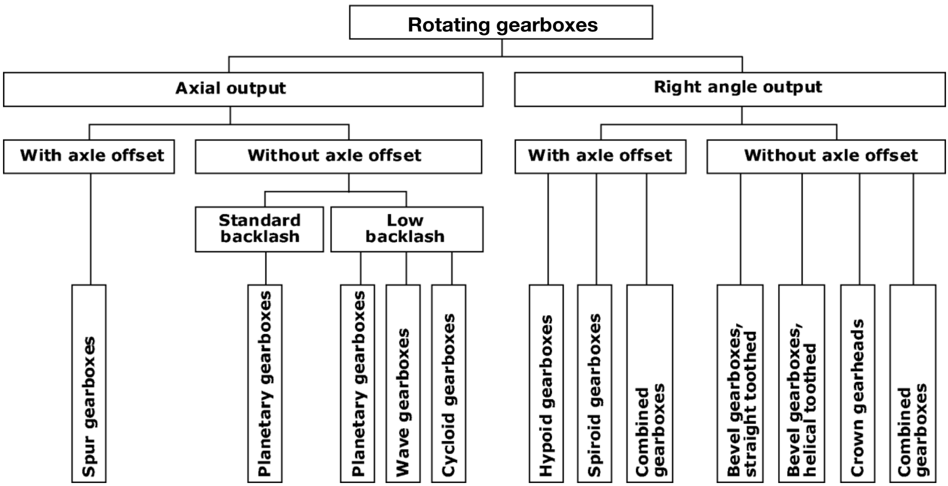


Figure 8 Gearbox types

Each gearbox type has its specific strengths and weaknesses. The optimum gearbox type is selected most easily by means of a form according to Table 39, which contains all suitable types of gearboxes.

The form allows selection in two steps: In the **first step**, all the gearbox types which cannot meet the technical requirements of the application, are eliminated. Technical exclusion criteria are used for this purpose. If a gearbox type cannot cover these criteria, it is excluded for the second step. In the upper part of Table 39 for each exclusion criterion it is marked, if the gearbox type meets the criterion (table field marked with an "x"), or if it doesn't (table field is empty).

In the **second step**, the remaining gearbox types are compared with each another and the optimum solution is determined. Performance criteria are used for this. In the lower part of Table 39, for each performance criterion it is indicated, how the gearbox type satisfies the criterion (table field is filled with a corresponding performance number).

The following exclusion criteria are used:

Gear ratio

Each gearbox type is available in a certain gear ratio range. If a larger or smaller gear ratio is required by the application, the gearbox type has to be eliminated. Some gearbox types may have the capability of self-locking or backing in certain ranges of the gear ratio. If these properties are required, the gear ratio valid in this case has to be used as exclusion criterion.

Output direction

In relation to the driving axis, the driven axis of the gearbox can either be axially or in right angle. Depending on the installation space available in the application, the required output direction must be selected.

Shaft type driven side

The output shaft can be designed either as a solid shaft or as a hollow shaft.

To exclude technically unsuitable gearbox types, select in the upper part of Table 39 in second column the criteria valid for the application. Enter the minimum and the maximum permissible value for the gear ratio. Then, go to the right in each selected row and delete all columns that are not marked with "x" or in which the requirements for the gear ratio are not covered (the corresponding fields are empty). The gearbox types in the deleted columns do not have to be considered in the following second selection step.

The following performance criteria are used:

Low backlash

When the torque changes its direction, only a small angular change occurs without traction between the driving side and the driven side.

Low overall length

A small overall length in the axial direction leads to a shorter motor-gear combination.

Low cross section

A small width leads to a gearbox that does not exeed the direction of the motor diameter.

Low axle offset

Input and output axes are in line and simplify the machine design.

Suitable for S1 operation

The gearbox is optimized for S1 operation (continuous operation).

Suitable for S5 operation

The gearbox is optimized for S5 operation (intermittent operation).

Long lifetime

The gearbox is designed for high mileages.

High efficiency

The gearbox is energy efficient.

High peak load

The gearbox can be heavily overloaded for a short time and is suitable for servo motors.

Low moment of inertia

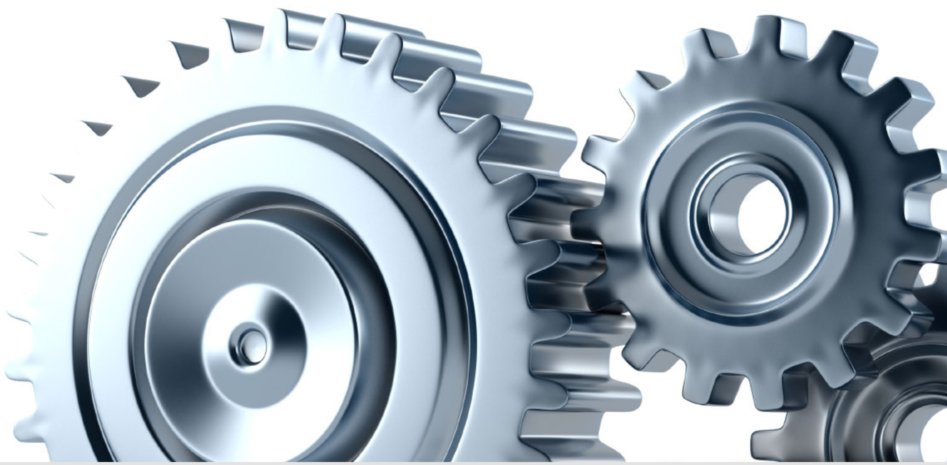
A low moment of inertia improves the acceleration capability of the motor.

High gear reduction per stage

High gear reduction per stage saves stages and improves efficiency.

Low noise

The gearbox runs quietly.



Low base friction

A low friction improves the efficiency and reduces the heating of the gearbox and the motor.

Low backing torque

The backing torque describes the torque that must be applied to the output shaft in order to keep the motor in rotation at a certain speed. This property is important for door motors in order to open the door manually in case of power loss.

Low cost/torque ratio

Self-locking effect

The gearbox cannot be reset and can therefore be used, for example, for linear actuators without brakes.

To select the optimum gearbox type from the technically suitable gearbox types, you have to define the priorities of the performance criteria for the application under consideration in the lower part of Table 39 in the second column. If the criterion is very important to you, set the value to 10.

If the criterion is unimportant, enter 0 for the priority. Then, move to the right in each selected row and multiply the priority by the performance number and enter the resulting score into the corresponding field.

If, for all technically suitable gearbox types, the scores for all performance criteria are determined, add these columns to a total score. The gearbox type with the highest overall score is the optimum gearbox type that should be selected for the application under consideration.

		Spur gearbox	Planetary gearbox	Planetary gearbox, low backlash	Wave gearbox	Cycloid gearbox	Worm gearbox	Helical gearbox
Exclusion criteria								
Gear ratio								
Without self-locking or backing								
8	Minimum gear ratio	2	3	3	28	28	3	3
22	Maximum gear ratio	100				32	80	24,5
With self-locking								
	Minimum gear ratio					28	40	
	Maximum gear ratio				32	32	80	
With backing								
X	Minimum gear ratio	2					3	3
	Maximum gear ratio	50					15	20
Output direction								
	Axially	x				x		
	Right angle						x	x
Shaft type driven side								
	Solid shaft	x	x	x	x	x	x	x
	Hollow shaft				x	x	x	x
Suitability								
Performance criteria								
Features								
	Low backlash	0	2	4	5	5	3	2
	Low overall length	5	2	2	5	5	3	3
	Low cross section	1	5	5	4	4	0	0
	Low axle offset	5	5	5	5	5	0	0
3	Suitable for S1 operation	1	4	5	5	5	**9**	1
	Suitable for S5 operation				5	5	3	3
	Long life time				5	5	3	2
	High efficiency	4	4	4	4	4	1	2
	High peak load	1					3	3
	Low moment of inertia	4					3	3
	High gear reduction per stage	2					5	4
	Low noise	3	3	3	3	3	5	4
	Low base friction	5	4	4	3	4	1	3
	Low backing torque	5	3	4	0	0	2	4
	Low cost/torque ratio	3					5	5
	Ranking						**34**	

Available gearbox types

Needed range of gear ratio

Minimum available gear ratio

Maximum available gear ratio

Gearbox type does not cover exclusion criterion

Gearbox type covers exclusion criterion

Selection of the required exclusion criteria
Choose one for each criterion.

Priority of performance criteria
0: not important to 10: very important

Performance number

Enter product from priority and performance number

Enter the sum of the points

Table 39 Form for selecting the optimum gearbox type

Spiroid gearbox	Hypoid gearbox	Bevel gearbox	Crown gearhead	Combination of planetary gearbox and bevel gearbox	Combination of planetary gear-box and worm gearbox	Combination of spur gear-box and bevel gearbox	Combination of planetary gear-box and bevel gearbox for high demands	Combination of planetary gear-box and crown gearhead
4	10	1	2	4,5	9	3	4,5	18
75	20	5	10	30	30	60	60	60
20								
75								
4	10	1	2	4,5	9	3	4,5	18
15	20	5	10	30	30	60	60	60
x	x	x	x	x	x	x	x	x
x	x	x	x	x	x	x	x	x
x	x				x			
2	4	3	2	2	3	4	4	3
2	2	3	3	2	2	2	3	5
3	4	3	1	3	1	4	5	5
3	4	5	5	5	1	3	5	5
5	5	3	1	3	3	4	5	3
5	5	3	3	3	3	4	5	4
5	5	2	1	2	3	4	4	3
2	3	4	4	4	2	4	4	4
3	3	3	1	3	3	3	3	4
3	3	3	3	5	5	4	5	5
5	3	2	3	2	4	3	2	3
5	5	2	2	3	3	3	3	3
1	2	4	5	4	1	3	4	4
3	3	4	5	4	2	3	4	4
2	1	2	2	2	2	2	0	2

Continuation Table 39

4.3.4 Selection of the gearbox

The gearbox is selected in two steps.

1. Selection of the gearbox according to mechanical characteristics
2. Selection of the gearbox according to thermal characteristics

When

- the motion sequences on the driven side are determined according to chapter 4.3.1,
- the gear ratio as defined according to chapter 4.3.2 and
- the optimum gearbox type is determined according to chapter 4.3.3,

the concrete gear is selected from the catalogue.

For this purpose, the relevant operating points of the load cycle are transferred into the characteristic diagram of the gearbox. The signs of the torque and the rotational speed are neglected.

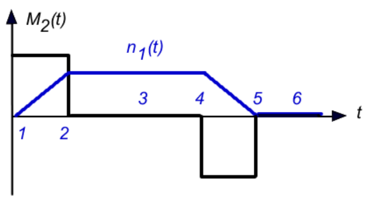
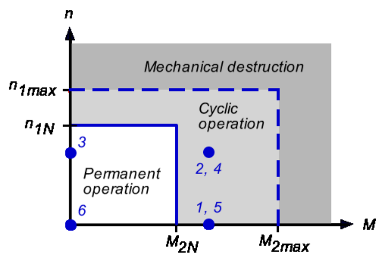
<table>
<tr><th>Load cycle</th><th colspan="2">Characteristics of the gearbox</th></tr>
<tr><td>
</td><td colspan="2">
</td></tr>
<tr><td>Selection condition</td><td>For all segments of the load cycle applies:</td><td>$n_1(t) < n_{1max}$
$M_2(t) < M_{2max}$</td></tr>
<tr><td colspan="3">M_{2N}: Rated torque driven side
M_{2max}: Maximum permissible torque driven side
n_{1N}: Rated speed driving side
n_{1max}: Maximum permissible speed driving side</td></tr>
</table>

Table 40 Selection of the gearbox according to mechanical characteristics

If all relevant operating points of the load cycle are located within the area limited by the characteristic for cyclic operation, the gearbox is suitable from a mechanical point of view. These gearboxes are pre-selected and further considered in the following selection steps. All other gearboxes are neglected. The energy conversion within the gearbox is subject to loss, which leads to temperature rise within the gearbox. It has to be ensured that the heating does not exceed the permissible limits. The permanent operation characteristic of the gearbox indicates the thermally permissible continuous torque as a function of the speed. Since variable speed motors and servo motors have a

temporally variable load, this must be converted to a continuous equivalent load. The continuous equivalent torque heats up the gearbox in the same way as the torque of the real load cycle.
The continuous equivalent torque or the equivalent operating point is described by the RMS value of the torque at the driven side and the mean absolute speed at the driving side.

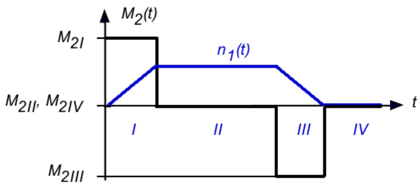
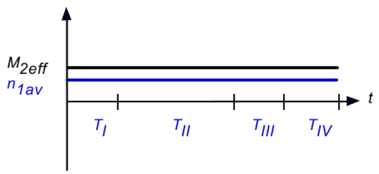
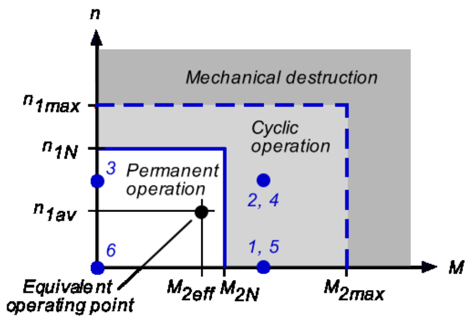
Load cycle	**Characteristics of the gearbox**
 **Continuous equivalent load causing same heating**  	
M_{2eff}: RMS value of the torque, general definition	$M_{2eff} = \sqrt{\frac{1}{T}\int_0^T M_2{}^2 dt}$
M_{2eff}: RMS value of the torque, simplified formula for segment wise constant torque at driven side	$M_{2eff} = \sqrt{\frac{M_{2I}{}^2 \cdot T_I + M_{2II}{}^2 \cdot T_{II} + M_{2III}{}^2 \cdot T_{III} + \cdots}{T_I + T_{II} + T_{III} + \cdots}}$
n_{1av}: Mean absolute speed, general definition	$n_{1av} = \frac{1}{T}\int_0^T \lvert n_1 \rvert dt$
Selection condition	The equivalent operating point is located within the area limited by the characteristic for permanent operation.
M_2: Torque driven side M_{2N}: Rated torque driven side M_{2max}: Maximum permissible torque driven side n_1: Speed driving side (1/s) n_{1N}: Rated speed driving side (1/s)	n_{1max}: Maximum permissible speed (1/s) driving side $M_{2I, 2II, 2III, 2IV}$: Torque driven side within segment I, II, III, IV $T_{I, II, III, IV}$: Duration of segment I, II, III, IV T: Duration of load cycle

Table 41 Selection of the gearbox according to thermal characteristics

If the equivalent operating point is located within the area limited by the characteristic for permanent operation, the corresponding gearbox is suitable from a thermal point of view the corresponding gearbox is suitable.

Of all gearboxes meeting the selection condition shown in Table 41, the smallest gearbox is selected. After selecting the gearbox, beside the speed n1 the torque profile M1 at the driving side can be determined according to Table 41. These two profiles are important input variables for selecting the motor.

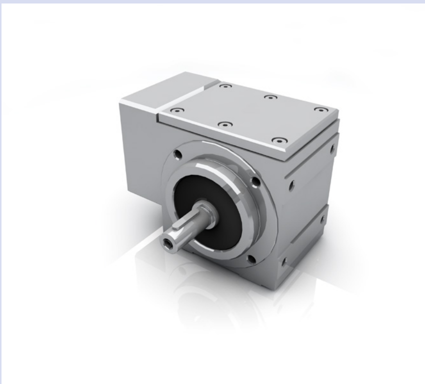
4.3.5 Gearboxes from Dunkermotoren

4.3.5.1 Planetary Gearboxes - Series PLG

Planetary gearboxes offer the highest continuous torque capacity of all types of gearboxes. The design is very compact, the weight is low and the efficiency is excellent. For planetary gearboxes from Dunkermotoren there are depending on customer requirements high-power, low-noise or low-backlash versions available. Continuous torques reach up to 160 Nm and the ratios vary from 3:1 to 710.5:1.

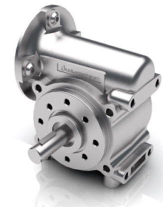
4.3.5.2 Spirotec Gearboxes - Series STG

Spirotec gearboxes are gearboxes with right angle output. Core element of the series STG is the spiral wheel set.
It enables reliable transmission of high torque with comparatively small centre distance in a small package. The Spirotec Gearbox is outstandingly quiet in operation and provides an unmatched long lifetime.



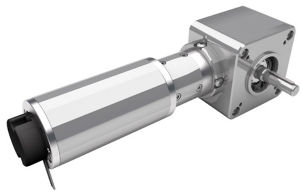
4.3.5.3 Worm/helical Gearboxes - Series SG

Worm/helical gearboxes are gearboxes with right angle output and noted for their very quiet running. The worm gear shaft has bearings on both sides and is available with different shaft positions or hollow shaft.



4.3.5.4 Bevel Gearboxes - Series KG

Bevel gearboxes are gearboxes with zero-offset right angle output. They have a high efficiency and allow in combination with planetary stages a wide range of gear ratios.



4.4 Example: Pump motor

After the plant has been configured and the pump has been selected, the required characteristics are available. They are entered into a common diagram.

Data of the pump at n = 2600 rpm										
Q in m^3/h	0,00	0,32	0,48	0,64	0,80	0,96	1,12	1,28	1,36	1,54
H in m	11,00	10,25	9,70	9,00	8,20	7,10	6,00	4,95	4,35	2,75
$\Delta p_P = H \cdot \rho \cdot g$ in kN/m^2	107,9	100,6	95,2	88,3	80,4	69,7	58,9	48,6	42,7	27,0
η	0,00	0,32	0,45	0,56	0,64	0,66	0,65	0,62	0,58	0,41
P_P in W	0,0	8,9	12,7	15,7	17,9	18,6	18,3	17,3	16,1	11,5
Data of the plant										
Δp_A in N/m^2	49,1	49,9	50,9	52,3	54,1	56,4	59,0	62,1	63,7	67,9

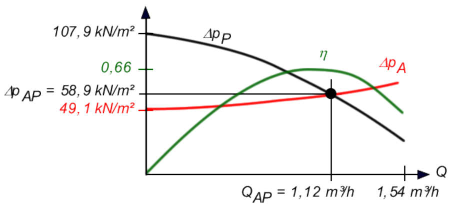
<table>
<tr><th>Characteristics of the pump</th><th colspan="2">The steady-state operating point is given by:</th></tr>
<tr><td rowspan="4">
</td><td>Volume flow</td><td>$Q_{AP} = 1{,}12\frac{m^3}{h} = 0{,}0003\frac{m^3}{s}$</td></tr>
<tr><td>Pressure difference</td><td>$\Delta p_{AP} = 58{,}9\ \frac{kN}{m^2}$</td></tr>
<tr><td>Efficiency</td><td>$\eta_{AP} = 0{,}65$</td></tr>
<tr><td>Conveying capacity</td><td>$P_{AP} = Q_{AP} \cdot \Delta p_{AP} = 17{,}7\ W$</td></tr>
<tr><td>P: Power at driving side, needed motor power</td><td colspan="2">$P = \frac{P_{AP}}{\eta_{AP}} = \frac{17{,}7\ W}{0{,}65} = 27{,}2\ W$</td></tr>
<tr><td>M: Torque at driving side, needed motor torque</td><td colspan="2">$M_M = \frac{P}{2\pi \cdot n} = \frac{27{,}2\ W \cdot min}{2\pi \cdot 2600} = 0{,}1\ Nm$</td></tr>
<tr><td colspan="3">Q: Volume flow of the heating water to be pumped
H: Discharge head of the pump
ρ: Density of heating water to be pumped (1000 kg/m³)
g: Acceleration due to gravity
Δp_P: Pressure difference of the pump (pump characteristic) at n=2800 rpm
η: Efficiency characteristic of the pump (pump characteristic) at n=2800 rpm
P_P: Conveying capacity of the pump (pump characteristic) at n=2800 rpm
Δp_A: Pressure difference of the plant (plant characteristic) at n=2800 rpm</td></tr>
</table>

Table 42 Operating point of a pump motor

The point of intersection of the pump and the system characteristic provides the steady-state operating point. No gearbox is used for the pump motor. The motion variables at the driven shaft of the pump are identical to the motion variables at the driving motor shaft.

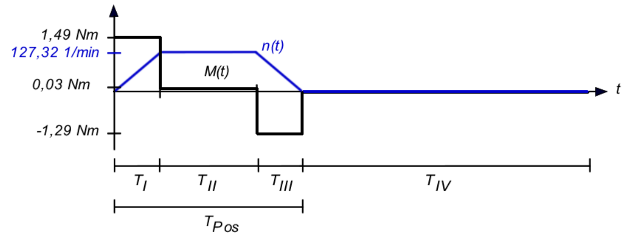
4.5 Example: Door motor

The mechanical system of the door motor consists of a wire rope pulling the elevator door. The following parameters are given:

Mass of door including bracket m_L: 90 kg • Mass of the wire rope m_{SZ}: 1,5 kg • Diameter of the deflection pulleys d_U: 0,06 m • Moment of inertia of a deflection pulley J_U: 0,0002 kgm² • Diameter of the support rolls d_S: 0,04 m • Moment of inertia of a support roll J_S: 0,00004 kgm² • Mass of a support roll m_S: 0,2 kg • Number of support rolls n_S: 2 • Rolling friction coefficient c_R: 0,0010 • Efficiency of the wire rope η: 0,95 • Desired rated speed of the motor n_N: 3000 1/min

The motion variables at the driving side of the wire rope can be determined using the motion variables calculated in chapter 3.6.

Motion variables at the driving side of the wire rope



Segment I, acceleration

Maximum angular speed	$\omega_{max} = v_{max} \cdot \frac{2}{d_U} = 0{,}4\frac{m}{s} \cdot \frac{2}{0{,}06m} = 13{,}33\frac{1}{s}$
Maximum speed	$n_{max} = v_{max} \cdot \frac{1}{\pi d_U} = 0{,}4\frac{m}{s} \cdot \frac{1}{\pi \cdot 0{,}06m} = 127{,}32\frac{1}{min}$
Angular acceleration	$\alpha = \alpha_{max} = a_{max} \cdot \frac{2}{d_U} = 0{,}5\frac{m}{s^2} \cdot \frac{2}{0{,}06m} = 16{,}67\frac{1}{s^2}$
Acceleration force of the load, the rope and the support rolls	$F_B = \left[m_L + m_{SZ} + n_S m_S + n_S J_S \frac{4}{{d_S}^2}\right] \cdot a_{max}$ $F_B = \left[90\ kg + 1{,}5\ kg + 2 \cdot 0{,}2\ kg + 2 \cdot 0{,}00004\ kgm^2 \frac{4}{(0{,}04\ m)^2}\right] \cdot 0{,}5\frac{m}{s^2} = 46{,}05\ N$
Friction force of the load (v > 0)	$F_R = c_R \cdot [m_L + n_S m_S] \cdot g = 0{,}001 \cdot [90\ kg + 2 \cdot 0{,}2\ kg] \cdot 9{,}81\frac{m}{s^2} = 0{,}89\ N$
Linear Force	$F = F_B + F_R = 46{,}05\ N + 0{,}89\ N = 46{,}94\ N$
Torque driving side, motor operation (F > 0, v > 0)	$M = 2 \cdot J_U \cdot \alpha_{max} + \left[F \cdot \frac{d_U}{2}\right] \cdot \frac{1}{\eta}$ $M = 2 \cdot 0{,}0002kgm^2 \cdot 16{,}67\frac{1}{s^2} + \left[46{,}94\ N \cdot \frac{0{,}06\ m}{2}\right] \cdot \frac{1}{0{,}95} = 1{,}49\ Nm$

Segment II, constant speed

Angular speed	$\omega = \omega_{max} = 13{,}33\frac{1}{s}$
Speed	$n = n_{max} = 127{,}32\frac{1}{min}$
Angular acceleration	$a = 0\frac{1}{s^2}$
Acceleration force of the load, the rope and the support rolls	$F_B = 0\ N$

Friction force of the load (v > 0)	$F_R = c_R \cdot [m_L + n_S m_S] \cdot g = 0{,}001 \cdot [90\,kg + 2 \cdot 0{,}2\,kg] \cdot 9{,}81\,\frac{m}{s^2} = 0{,}89\,N$
Linear Force	$F = F_R = 0\,N + 0{,}89\,N = 0{,}89\,N$
Torque driving side, motor operation (F > 0, v > 0)	$M = \left[F \cdot \frac{d_U}{2}\right] \cdot \frac{1}{\eta} = \left[0{,}89\,N \cdot \frac{0{,}06\,m}{2}\right] \cdot \frac{1}{0{,}95} = 0{,}03\,Nm$
Segment III, deceleration	
Maximum angular speed	$\omega = \omega_{max} = v_{max} \cdot \frac{2}{d_U} = 0{,}4\,\frac{m}{s} \cdot \frac{2}{0{,}06m} = 13{,}33\,\frac{1}{s}$
Maximum speed	$n_{max} = v_{max} \cdot \frac{1}{\pi d_U} = 0{,}4\,\frac{m}{s} \cdot \frac{1}{\pi \cdot 0{,}06m} = 127{,}32\,\frac{1}{min}$
Angular acceleration	$\alpha = -\alpha_{max} = -a_{max} \cdot \frac{2}{d_U} = -0{,}5\,\frac{m}{s^2} \cdot \frac{2}{0{,}06m} = -16{,}67\,\frac{1}{s^2}$
Acceleration force of the load, the rope and the support rolls	$F_B = \left[m_L + m_{SZ} + n_S m_S + n_S J_S \frac{4}{{d_S}^2}\right] \cdot (-a_{max})$ $F_B = \left[90\,kg + 1{,}5kg + 2 \cdot 0{,}2kg + 2 \cdot 0{,}00004\,kgm^2 \frac{4}{(0{,}04\,m)^2}\right] \cdot (-0{,}5)\,\frac{m}{s^2} = -46{,}05\,N$
Friction force of the load (v > 0)	$F_R = c_R \cdot [m_L + n_S m_S] \cdot g = 0{,}001 \cdot [90\,kg + 2 \cdot 0{,}2\,kg] \cdot 9{,}81\,\frac{m}{s^2} = 0{,}89\,N$
Linear Force	$F = F_B + F_R = -46{,}05\,N + 0{,}89\,N = -45{,}14\,N$
Torque driving side, generator operation (F < 0, v > 0)	$M = 2 \cdot J_U \cdot (-\alpha_{max}) + \left[F \cdot \frac{d_U}{2}\right] \cdot \eta$ $M = 2 \cdot 0{,}0002kgm^2 \cdot \left(-16{,}67\,\frac{1}{s^2}\right) + \left[-45{,}14\,N \cdot \frac{0{,}06\,m}{2}\right] \cdot 0{,}95 = -1{,}29\,Nm$
Segment IV, pause	
Angular speed	$\omega = 0\,\frac{1}{s}$
Speed	$n = 0\,\frac{1}{min}$
Angular acceleration	$a = 0\,\frac{1}{s^2}$
Acceleration Force of the load, the rope and the support rolls	$F_B = 0\,N$
Friction force of the load (v > 0)	$F_R = 0\,N$
Linear Force	$F = 0\,N$

Table 43 Motion variables of the wire rope for a door motor

The motion variables for the driving side of the wire rope do not match the typical characteristics of an electric motor. Therefore, a rotating gearbox is required. The possible range of the gear ratio must be determined first. According to the task, the maximum speed at the driving side should be less than 3000 rpm. This results in a maximum value for the gear ratio of

$$i_{max} = \frac{n_{1max}}{n_{2max}} = \frac{3000\ \frac{1}{min}}{127{,}32\ \frac{1}{min}} = 23{,}56$$

With this specification, the optimum gearbox type can be determined. For this purpose in the first step the technically suitable gearbox types are extracted. According to Table 46, the following gearbox types are suitable: • Helical gearbox • Hypoid gearbox • Combination of planetary gearbox and bevel gearbox • Combination of planetary gearbox and worm gearbox • Combination of spur gearbox and bevel gearbox • Combination of planetary gearbox and bevel gearbox for high demands. For the second step, the requirements of the application are weighted and the priorities are assigned:

Performance criterion	Priority	Reason
Low backlash	2	No high priority, since very high accuracy is not required.
Low overall length	2	No high priority, since a right-angle gearbox is used.
Low cross section	2	No high priority, since a right-angle gearbox is used.
Low axle offset	0	The axle offset is not important.
Suitable for S1 operation	0	Continuous operation is not needed.
Suitable for S5 operation	1	Intermittent operation is required but is not a high priority.
Long lifetime	5	The motor is only used sporadically.
High efficiency	5	High efficiency is desired.
High peak load	2	The gearbox is not exposed to very high torque peaks.
Low moment of inertia	1	The inherent moment of inertia of the gearbox has a low influence due to the high mass of the door.
High gear reduction per stage	5	High reduction per stage improves efficiency.
Low noise	10	Since the elevator is used in the living area, a low noise level is very important.
Low base friction	2	The basic friction plays a minor role.
Low backing torque	10	The backing torque plays an important role for a door motor.
Low cost/torque ratio	10	Since it is a series application, low cost for the gear box is very important.

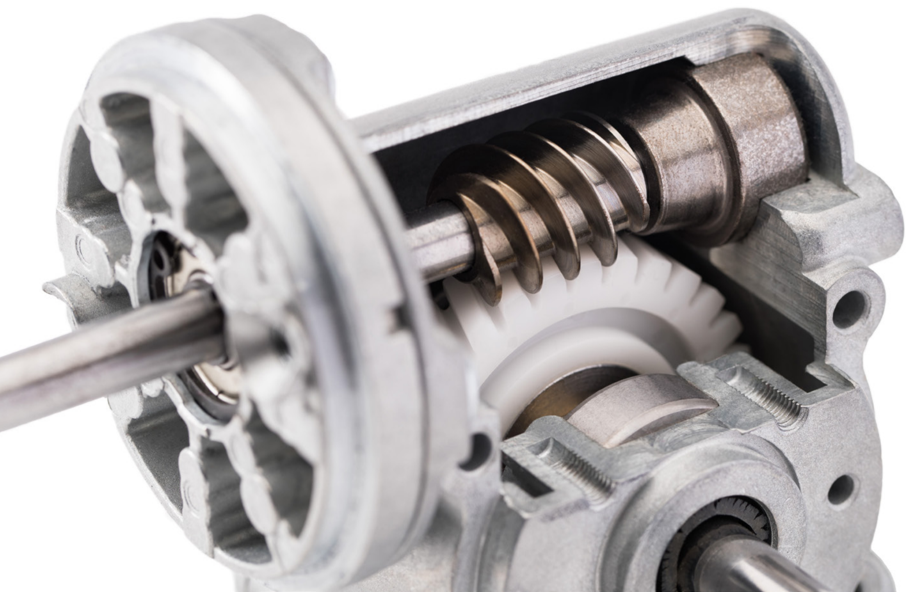
Table 44 Prioritisation of the performance criteria for selecting the optimum gearbox type for a door motor

This results in the following scores for the suitable gearbox types:

Gearbox type	Score
Helical gearbox	198
Hypoid gearbox	183
Combination of planetary gearbox and bevel gearbox	166
Combination of planetary gearbox and worm gearbox	143
Combination of spur gearbox and bevel gearbox	175
Combination	168

Table 45 Ranking of gearbox types for a door motor

The optimum gearbox type is thus a helical gearbox.



			Spur gearbox	Planetary gearbox	Planetary gearbox, low backlash	Wave gearbox	Cycloid gearbox	Worm gearbox	Helical gearbox
Exclusion criteria	Gear ratio								
	Without self-locking or backing								
		Minimum gear ratio	2	3	3	28	28	3	3
		Maximum gear ratio	100	200	200	32	32	80	24,5
	With self-locking								
		Minimum gear ratio				28	28	40	
		Maximum gear ratio				32	32	80	
	With backing								
	15	Minimum gear ratio	2	3	3			3	3
	20	Maximum gear ratio	50	50	50			~~15~~	20
	Output direction								
		Axially	x	x	x	x	x		
	x	Right angle						x	x
	Shaft type driven side								
	x	Solid shaft	x	x	x	x	x	x	x
		Hollow shaft				x	x	x	x
	Suitability								
Performance criteria	Features								
	2	Low backlash	0	2	4	5	5	3	**4**
	2	Low overall length	5	2	2	5	5	3	**6**
	2	Low cross section	1	5	5	4	4	0	**0**
	0	Low axle offset	5	5	5	5	5	0	**0**
	0	Suitable for S1 operation	1	4	5	5	5	3	**0**
	1	Suitable for S5 operation	2	4	4	5	5	3	**3**
	5	Long life time	1	3	5	5	5	3	**10**
	5	High efficiency	4	4	4	4	4	1	**10**
	2	High peak load	1	4	4	4	4	3	**6**
	1	Low moment of inertia	4	5	2	1	1	3	**3**
	5	High gear reduction per stage	2	4	3	5	5	5	**20**
	10	Low noise	3	3	3	3	3	5	**40**
	2	Low base friction	5	4	4	3	4	1	**6**
	10	Low backing torque	5	3	4	0	0	2	**40**
	10	Low cost/torque ratio	3	5	3	1	1	5	**50**
		Ranking							**198**

Table 46 Form for selecting the optimum gearbox type for a door motor

Spiroid gearbox	Hypoid gearbox	Bevel gearbox	Crown gearhead	Combination of planetary gearbox and bevel gearbox	Combination of planetary gear-box and worm gearbox	Combination of spur gear-box and bevel gearbox	Combination of planetary gear-box and bevel gearbox for high demands	Combination of planetary gear-box and crown gearhead
4	10	1	2	4,5	9	3	4,5	18
75	20	5	10	30	30	60	60	60
20								
75								
4	10	1	2	4,5	9	3	4,5	~~18~~
~~15~~	20	~~5~~	~~10~~	30	30	60	60	60
x	x	x	x	x	x	x	x	x
x	x	x	x	x	x	x	x	x
x	x				x			
2	**8**	3	2	**4**	**6**	**8**	**8**	3
2	**4**	3	3	**4**	**4**	**4**	**6**	5
3	**8**	3	1	**6**	**2**	**8**	**10**	5
3	**0**	5	5	**0**	**0**	**0**	**0**	5
5	**0**	3	1	**0**	**0**	**0**	**0**	3
5	**5**	3	3	**3**	**3**	**4**	**5**	4
5	**25**	2	1	**10**	**15**	**20**	**20**	3
2	**15**	4	4	**20**	**10**	**20**	**20**	4
3	**6**	3	1	**6**	**6**	**6**	**6**	4
3	**3**	3	3	**5**	**5**	**4**	**5**	5
5	**15**	2	3	**10**	**20**	**15**	**10**	3
5	**50**	2	2	**30**	**30**	**30**	**30**	3
1	**4**	4	5	**8**	**2**	**6**	**8**	4
3	**30**	4	5	**40**	**20**	**30**	**40**	4
2	**10**	2	2	**20**	**20**	**20**	**0**	2
	183			**166**	**143**	**175**	**168**	

Continuation Table 46

For the preselection of the gearbox, the maximum occurring torque and the RMS value of the torque at the driven side are considered.

Maximum torque driven side	$M_{2max} = 1{,}49\ Nm$
RMS value of the torque driven side	$M_{2eff} = \sqrt{\frac{(1{,}49\ Nm)^2 \cdot 0{,}8s + (0{,}03\ Nm)^2 \cdot 1{,}7s + (-1{,}29\ Nm)^2 \cdot 0{,}8s}{8{,}3\ s}} = 0{,}612\ Nm$

With these characteristic values, a gearbox can be selected from the following worm or helical gearbox series.

Data/ Technische Daten | SG 80 | SG 80 H | SG 80 K								
Reduction ratio/ Untersetzungsverhältnis	SG 80 / SG 80 H	5	10	15	24	38	50	75
Efficiency/ Wirkungsgrad	%	70	65	55	50	40	35	25
Continuous torque/ Dauerdrehmoment	Ncm	200	250	350	350	350	400	400
Max.acceleration torque/ Max. Beschleunigungsmoment	Ncm	800						
Emergency torque/ Not-Aus Drehmoment	Ncm	1200						
Operating mode/ Betriebsart	-	S1 / S5*						
Reduction ratio/ Untersetzungsverhältnis	SG 80 K	7	10	15	24.5	-	-	-
Efficiency/ Wirkungsgrad	%	82	80	70	65	-	-	-
Continuous torque/ Dauerdrehmoment	Ncm	250	250	350	350	-	-	-
Max.acceleration torque/ Max. Beschleunigungsmoment	Ncm	500	500	700	700			
Emergency torque/ Not-Aus Drehmoment	Ncm	1200						
Operating mode/ Betriebsart	-	S5*						
Weight of gearbox/ Getriebegewicht	kg	0.9						
Axial load / radial load/ Axiallast / Radiallast	N	300 / 350						

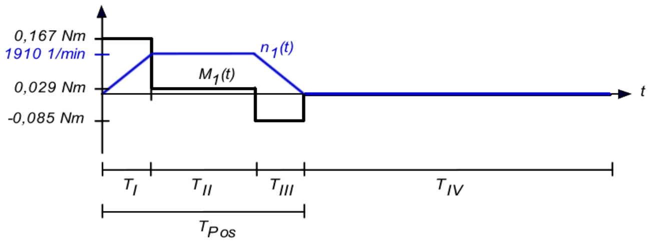
Figure 9 Excerpt from a catalogue for helical gearboxes

The gearbox has a rated torque of 3.5 Nm and a permissible maximum torque of 7.0 Nm. Therefore:

$M_{2eff} < M_N$	$0{,}612\ Nm < 3{,}5\ Nm$
$M_{2max} < M_{max}$	$1{,}49\ Nm < 7{,}0\ Nm$
$i < i_{max}$	$15 < 23{,}56$

All characteristic values are within the permissible range. The selected gearbox is suitable and can be used. The moment of inertia "J" of the gearbox is 0.0001 kgm².
Together with the motion variables from Table 43, the motion variables at the driving side of the gearbox can be determined.

Motion variables at the driving side of the wire rope



Segment I, acceleration	
Maximum angular speed	$\omega_{max1} = \omega_{max2} \cdot i = 13{,}33\frac{1}{s} \cdot 15 = 200\frac{1}{s}$
Maximum speed	$n_{max1} = n_{max2} \cdot i = 127{,}32\frac{1}{min} \cdot 15 = 1910\frac{1}{min}$
Angular acceleration	$\alpha_1 = \alpha_{max1} = a_{max2} \cdot i = 16{,}67\frac{1}{s^2} \cdot 15 = 250\frac{1}{s^2}$
Torque driving side, motor operation $(M_2 > 0,\ \omega_2 > 0)$	$M_1 = J \cdot \alpha_1 + \frac{M_2}{i} \cdot \frac{1}{\eta} = 0{,}0001\ kgm^2 \cdot 250\frac{1}{s^2} + \frac{1{,}49\ Nm}{15} \cdot \frac{1}{0{,}7} = 0{,}167\ Nm$
Segment II, constant speed	
Angular speed	$\omega_1 = \omega_{max1} = 200\frac{1}{s}$
Speed	$n_1 = n_{max1} = 1910\frac{1}{min}$
Angular acceleration	$\alpha_1 = 0\frac{1}{s^2}$
Torque driving side, motor operation $(M_2 > 0,\ \omega_2 > 0)$	$M_1 = \frac{M_2}{i} \cdot \frac{1}{\eta} = \frac{0{,}03\ Nm}{15} \cdot \frac{1}{0{,}7} = 0{,}0029\ Nm$
Segment III, deceleration	
Maximum angular speed	$\omega_{max1} = \omega_{max2} \cdot i = 13{,}33\frac{1}{s} \cdot 15 = 200\frac{1}{s}$
Maximum speed	$n_{max1} = n_{max2} \cdot i = 127{,}32\frac{1}{min} \cdot 15 = 1910\frac{1}{min}$
Angular acceleration	$\alpha_1 = -\alpha_{max1} = -a_{max2} \cdot i = -16{,}67\frac{1}{s^2} \cdot 15 = -250\frac{1}{s^2}$
Torque driving side, generator operation $(M_2 < 0,\ \omega_2 > 0)$	$M_1 = J \cdot (-\alpha_{max1}) + \frac{M_2}{i} \cdot \eta = 0{,}0001\ kgm^2 \cdot \left(-250\frac{1}{s^2}\right) - \frac{1{,}29\ Nm}{15} \cdot 0{,}7 = -0{,}085\ Nm$

Segment IV, pause	
Angular speed	$\omega_1 = 0\frac{1}{s}$
Speed	$n_1 = 0\frac{1}{min}$
Angular acceleration	$\alpha_1 = 0\frac{1}{s^2}$
Torque driving side	$M_1 = 0\,Nm$
RMS value torque	
RMS value torque driving side	$M_{1eff} = \sqrt{\frac{(0{,}167\,Nm)^2 \cdot 0{,}8s + (0{,}0029\,Nm)^2 \cdot 1{,}7s + (-0{,}085\,Nm)^2 \cdot 0{,}8s}{8{,}3\,s}} = 0{,}058\,Nm$

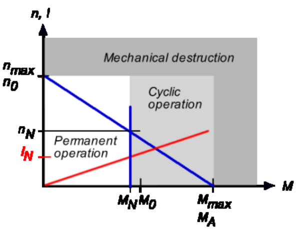
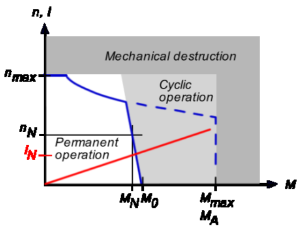
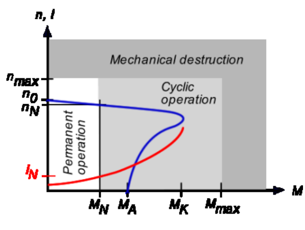
Table 47 Motion variables at the driving side of the gearbox for a door motor

5 Design of the motor

5.1 Characteristics of electrical motors

If the motion sequence at the motor shaft is determined, a specific motor is selected from the catalogue. The selection is made taking into account the electrical, mechanical and thermal characteristics of the motor, which are represented by characteristics.

The characteristics differ from each motortype. However, the characteristic parameters relevant for the selection of the motor are uniformly defined.

DC motor on DC grid	Brushless DC motor on servo amplifier with closed loop control	Asynchronous motor on AC grid
		

Characteristic		Description
U_N :	Rated voltage	The voltage applied to the motor. All rated values in the catalogues refer to this voltage. However, the motor is not limited to this voltage.
I_N:	Rated current	The absorption current flowing through the motor if operated at rated torque and rated speed.
M_N:	Rated torque	The torque, the motor can provide permanently at rated ambient temperature during operation at rated speed without overheating.
M_A:	Start-up torque	The maximum torque, the motor provides at standstill. The start-up torque can deviate from its theoretical value if the control unit limits the current or the motor has been demagnetized.
M_{max}:	Maximum torque	The torque at which the motor can be operated at its maximum taking into account the pulse controller and demagnetization
M_K:	Stall torque	The maximum torque an asynchronous motor can provide if it is operated on a 1-phase or 3-phase AC grid.
n_N:	Rated speed	The speed of the motor which results during operation at rated voltage and rated torque.
n_0:	No-load speed	The speed of the motor which results during operation without load at rated voltage. The no-load speed may deviate from its theoretical value if friction occurs in the bearings of the motor shaft or due to a fan attached to the motor shaft.
n_{max}:	Maximum speed	The speed at which the motor can be operated at its maximum without mechanical damage.
P_N:	Rated power	The mechanical output power of the motor can provide permanently at rated ambient temperature without overheating. It is calculated from rated speed and rated torque.
P_{max}:	Maximum power	The maximum mechanical output power, the motor can provide for a short time.
k_T:	Torque constant	The ratio between the motor current and the motor torque. The torque constant is used in brushed DC motors, brushless DC motors and synchronous motors.
M_R:	Friction torque	Torque, which must be overcome if the current-less motor is driven from outside.

Table 48 Characteristics for electrical motors

Depending on the application the selection of the motor takes place in two different ways:

- Constant speed motors: Selection according to speed and power requirements
- Variable speed motors and servo motors: Selection according to speed and torque requirements with motor recalculation and thermal verification

5.2 Constant speed motors

Constant speed motors are operated directly on the DC or AC voltage grid and run at fixed speed. Neglecting the start-up, no speed changes and thus no acceleration and deceleration phases have to be taken into account. The selection of the motor can be done most easily by consideration of the operating point the motor is running at.

5.2.1 Constant speed motors with permanent magnet DC motor

If a permanent magnet DC motor is operated at a constant supply voltage under steady state conditions, its behaviour can be described by the following equations. The DC motor is selected basing on the operating point at which the constant motor is running.

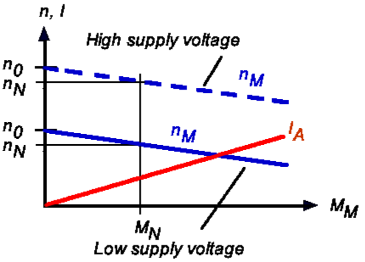
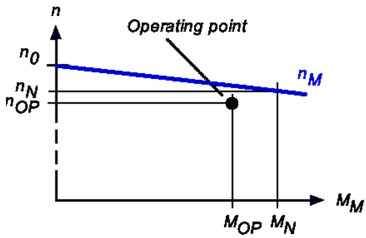
Characteristics of the DC motor	
 	
Selection conditions	$M_{AP} \leq M_N$ $n_{AP} \leq n_N$
n_M: Motor speed	$n_M = \left[\frac{U_A}{k_T} - \frac{R_A}{{k_T}^2} M_M\right] \frac{1}{2\pi}$
M_M: Motor torque	$M_M = I_A \cdot k_T$
U_A: Armature voltage (supply voltage)	$U_A = R_A \cdot I_A + U_M$
U_M: Motor voltage (EMF)	$U_M = k_T \cdot 2\pi \cdot n$
I_{Anlauf}: Start-up current at n=0	$I_{Anlauf} = \frac{R_A}{U_A}$
P_1: Electrical power	$P_1 = U_A \cdot I_A$
P_2: Mechanical power at motor shaft	$P_2 = M_M \cdot 2\pi \cdot n$
P_{Verl}: Power dissipation in the armature winding	$P_{Verl} = R_A \cdot {I_A}^2$
η: Efficiency	$\eta = \frac{P_2}{P_1}$
n_0: No-load speed (1/s) n_N: Rated speed (1/s) n_{AP}: Motor speed at operating point (1/s) k_T: Torque constant	M_N: Rated torque M_{AP}: Motor torque at operating point I_A: Armature current R_A: Armature resistance

Table 49 Equations of the DC motor in steady-state operation

It should be noted that the supply voltage can be selected within a certain permissible range. If the winding insulation of the motors is designed accordingly, these motors can be operated, for example, at supply voltages of 12 V or 24 V. A separate characteristic diagram applies to each of these supply voltages. As the supply voltage increases, the speed-torque characteristic of the permanent magnet DC motor is shifted upwards. The no-load speed and the power of the motor increase approximately proportionally to the supply voltage.

If a permanent magnet DC motor in standstill is connected to the DC voltage, high start-up current flows. This can be limited by additional series resistors, which are bypassed successively. By selecting the resistance stages, the peak values of the torque and the start-up current can be adjusted as required

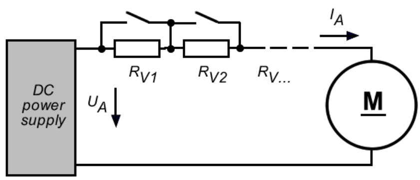
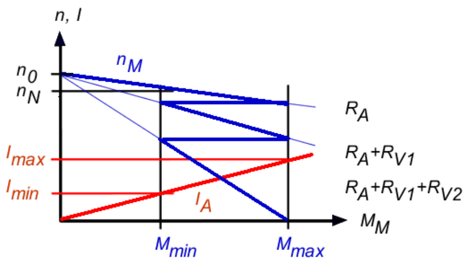
Start-up circuit with series resistors	**Characteristics of the DC motor**
	
λ: Switching ratio	$\lambda = \frac{M_{max}}{M_{min}} = \frac{I_{max}}{I_{min}}$
z: Number of switching stages	$z = \frac{ln\left[\frac{R_A+R_{V\Sigma}}{R_A}\right]}{ln(\lambda)}$
R_{V1}: Series resistor 1	$R_{V1} = R_A(\lambda - 1)$
R_{V2}: Series resistor 2	$R_{V2} = (R_A + R_{V1}) \cdot (\lambda - 1)$
R_{Vn}: Series resistor n	$R_{Vn} = (R_A + R_{V1} + \cdots + R_{V(n-1)}) \cdot (\lambda - 1)$
$R_{V\Sigma}$: Sum of series resistors	$R_{V\Sigma} = \left(R_{V1} + \cdots + R_{Vz)}\right) = \frac{U_A \cdot k_T}{M_{max}} - R_A$
P_{Verl}: Power dissipation in the series resistors	$P_{Verl} = I_{max} \cdot I_{min} \cdot R_{V\Sigma}$
n_0: No-load speed n_N: Rated speed M_{max}: Maximum motor torque at start-up M_{min}: Minimum motor torque at start-up	I_A: Armature current I_{max}: Maximum armature current at start-up I_{min}: Minimum armature current at start-up R_A: Armature resistance k_T: Torque constant

Table 50 Equations of the DC motor in steady-state operation with series resistors

5.2.2 Constant speed motors with asynchronous motor

If an asynchronous motor is operated on a 1-phase or 3-phase AC grid under steady-state conditions its behaviour can be described by the following equations:

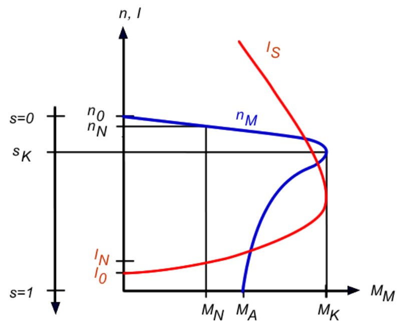
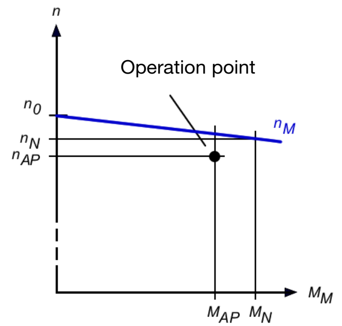
Characteristics of the asynchronous motor		
		
Selection conditions		$M_{AP} \leq M_N$ $n_{AP} \leq n_N$
s:	Slip	$s = \frac{n_0 - n}{n_0}$
n_0:	No-load speed	$n_0 = \frac{fn}{p}$
M_M:	Motor torque	$\frac{M_M}{M_K} = \frac{2}{\frac{s_K}{s} + \frac{s}{s_K}}$
P_{el}:	Electrical power (active power)	$P_{el} = \sqrt{3} U_N I_N \cdot \cos(\varphi)$
P_{mech}:	Mechanical power at motor shaft	$P_{mech} = M_M \cdot 2\pi \cdot n$
η:	Efficiency	$\eta = \frac{P_{mech}}{P_{el}}$
p: Polpair number of the motor f_N Frequency of the grid U_N: Voltage amplitude of the grid n_0: No-load speed (1/s) n_N: Rated speed (1/s) n_{AP}: Motor speed at operating point s_K: Stall slip		φ: Power factor I_S: Stator current I_0: No-load current M_N: Rated torque M_A: Start-up torque M_K: Stall torque M_{AP}: Motor torque at operating point

Table 51 Equations of the asynchronous motor in steady-state operation

The asynchronous motor is selected basing on the operating point at which the constant motor is running. If a 3-phase asynchronous motor in standstill is connected to the AC grid, high start-up current flows. This can be reduced to 1/3 by a star-delta start-up circuit. The star-delta start-up circuit can be used for 3-phase asynchronous motors whose rated voltage in delta connection is equal to the grid voltage at which the motor has to be operated and which must only start-up against a low load torque.

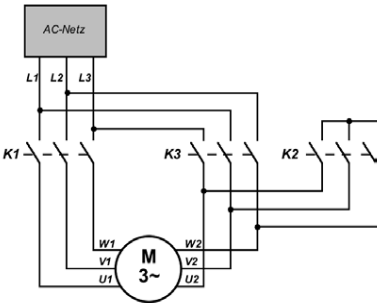
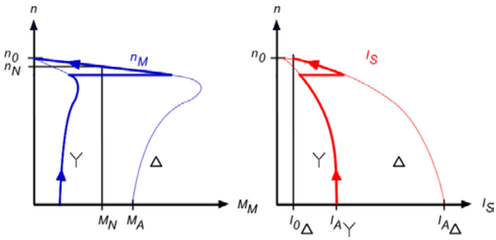
Star-delta start-up	**Characteristics of the asynchronous motor**
	
Wiring of the motor during start-up	Star connection
Wiring of the motor during operation	Delta connection
Lowering start-up current in star connection to	$\frac{1}{3}$
Lowering start-up motor torque in star connection to	$\frac{1}{3}$
n_0: No-load speed n_N: Rated speed M_N: Rated torque M_A: Start-up torque	I_S: Stator current I_0: No-load current I_A: Start-up current

Table 52 Equations of the asynchronous motor in steady-state operation with star-delta start-up circuit

5.3 Variable speed motors and Servo motors

5.3.1 Selection of the motor according to mechanical parameters

The selection according to mechanical parameters is carried out in two steps:

1. Preselection of the motor
2. Recalculation considering the moment of inertia of the motor

If the motion sequence at the driving side of the gearbox and thus at the motor shaft are determined in accordance with chapter 4, the motor is selected from the catalogue in the first step. For this purpose, the relevant operating points of the load cycle are transferred into the characteristic diagram of the motor. The signs of the torque and the speed are neglected.

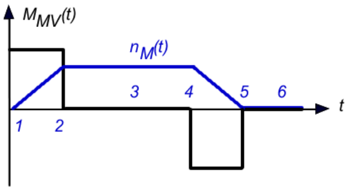
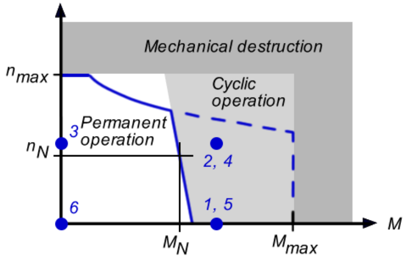
Load cycle	Characteristics of the motor
	
Selection condition	All relevant operating points are located within the area limited by the characteristic for cyclic operation.
M_{MV}: Motor torque for preselection of the motor n_M: Motor speed	M_N: Rated torque of the motor M_{max}: Maximum torque of the motor n_N: Rated speed of the motor n_{max}: Maximum speed of the motor

Table 53 Preselection of the motor according to mechanical parameters

If all relevant operating points of the load cycle are located within the area limited by the characteristic for cyclic operation, the motor is suitable from a mechanical point of view. These motors are preselected and further considered in the following selection steps. All other motors are neglected. In the motor recalculation, the moment of inertia of the motor is additionally taken into account.

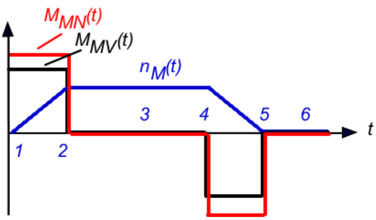
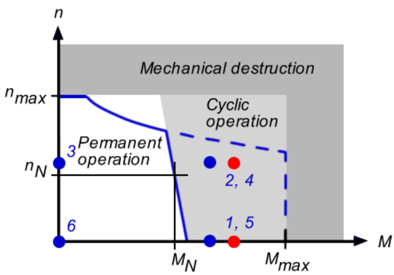
Load cycle	Characteristics of the motor
	
M_{MN}: Motor torque for recalculation of the motor	$M_{MN} = J_M \frac{d\omega}{dt} + M_{MV}$
Selection condition	All relevant operating points are located within the area limited by the characteristic for cyclic operation.
M_{MV}: Motor torque for preselection of the motor n_M: Motor speed M_N: Rated torque of the motor	M_{max}: Maximum torque of the motor n_N: Rated speed of the motor n_{max}: Maximum speed of the motor J_M: Moment of inertia of the motor

Table 54 Motor recalculation

In each segment of the load cycle where acceleration or deceleration occurs, the torque applied by the motor changes. As a result, there is a corrected load cycle whose relevant operating points are again transferred to the characteristic diagram of the motor. If all relevant operating points of the load cycle are still located within the area limited by the characteristic for cyclic operation the motor is finally suitable from a mechanical point of view.

This motor is selected and further considered in the following selection steps. If some operating points are now outside the area limited by the characteristic for cyclic operation, the preselected motor is not suitable. These motors are neglected and no longer included in the following selection steps. The selection according to mechanical parameters is thus completed.

5.3.2 Selection of the motor according to thermal characteristics

The energy conversion within the motor is subject to loss, which leads to temperature rise within the motor. It has to be ensured that the heating does not exceed the permissible limits according to Table 55.

Thermal class according to DIN-VDE 0530 (IEC 60085)	A	E	B	F	H
Maximum permissible motor temperature at the hottest point of the winding in °C	105	120	130	155	180
Average permissible motor temperature in °C	100	115	120	140	165
Permissible over temperature at an ambient temperature of 40 °C	60	75	80	100	125

Table 55 Limits of motor heating

When the motor is loaded, its temperature increases with a time delay. The time delay is determined by the thermal time constant of the motor.

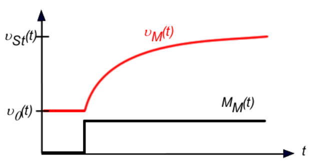
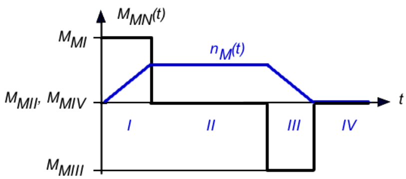
	Motor temperature	$\vartheta_M = \vartheta_0 + \vartheta_{Ov}\left[1 - e^{-\frac{t}{T_{th}}}\right]$
	After $t=3 \cdot T_{th}$, the motor reached 95 % of its steady-state over temperature.	
ϑ_0: Ambient temperature ϑ_{St}: Final steady-state temperature	ϑ_{Ov}: Over temperature T_{th}: Thermal time constant of the motor	

Table 56 Temperature response of the loaded motor

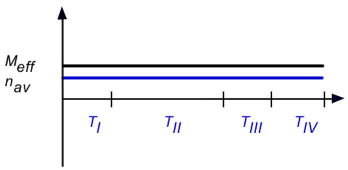
The permanent load characteristic curve of the motor indicates the thermally permissible continuous torque as a function of the speed. Since variable speed motors and servo motors have a temporally variable load, this must be converted to a continuous equivalent load or an equivalent operating point. The continuous equivalent torque heats the motor in the same way as the torque of the real load cycle. The continuous equivalent torque and the equivalent operating point are described by the RMS value of the torque and the average absolute speed.

<table>
<tr><th>Load cycle</th><th>Characteristics of the motor</th></tr>
<tr><td>

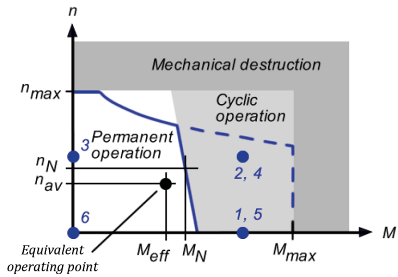


</td><td></td></tr>
<tr><td>

Continuous equivalent load causing same heating



</td><td>



</td></tr>
<tr><td>M_{eff}: RMS value of the torque, general definition</td><td>

$$M_{eff} = \sqrt{\frac{1}{T}\int_0^T {M_M}^2 dt}$$

</td></tr>
<tr><td>M_{eff}: RMS value of the torque, simplified formula for segment wise constant motor torque</td><td>

$$M_{eff} = \sqrt{\frac{{M_{MI}}^2 \cdot T_I + {M_{MII}}^2 \cdot T_{II} + {M_{MIII}}^2 \cdot T_{III} + \cdots}{T_I + T_{II} + T_{III} + \cdots}}$$

</td></tr>
<tr><td>n_{av}: Mean absolute speed, general definition</td><td>

$$n_{av} = \frac{1}{T}\int_0^T |n_M| dt$$

</td></tr>
<tr><td>

Selection condition
Boundary condition: $T \leq 0{,}1 \cdot T_{th}$

</td><td>The equivalent operating point is located within the area limited by the characteristic for permanent operation</td></tr>
<tr><td>

M_{MN}: Motor torque determined during motor recalculation
n_M: Motor speed (1/s)
M_N: Rated torque of the motor
M_{max}: Maximum torque of the motor

</td><td>

n_N: Rated speed of the motor (1/s)
n_{max}: Maximum speed of the motor (1/s)
$M_{I,\,II,\,III,\,IV}$: Motor torque within segment I, II, III, IV
$T_{I,\,II,\,III,\,IV}$: Duration of segment I, II, III, IV
T: Duration of load cycle
T_{th}: Thermal time constant of the motor

</td></tr>
</table>

Table 57 Selection of the motor according to thermal characteristics

If the equivalent operating point of the load cycle is located within the area limited by the characteristic for permanent operation the motor is suitable from a thermal point of view.

If the boundary condition $T \leq 0{,}1 \cdot T_{th}$ is not fulfilled, all relevant operating points of the load cycle have to be located within the area limited by the characteristic for permanent operation. This approach guarantees a safe motor selection, but may lead to an over sizing in some cases. In uncertain cases, a simulation of the thermal behaviour of the motor is recommended or carry out tests in the actual application.

5.3.3 Selection of the encoder

For speed and position measurement, encoders are used in variable speed motors and servo motors. Depending on the number of pulses per revolution, the number of tracks, and depending on the design of the encoder electronics, different accuracies can be reached for speed and position measurement at the motor shaft.

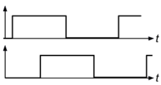
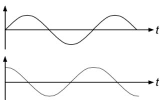
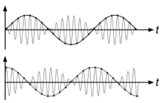
Encoder	Signal shape	Rotational direction detectable	Resolution of position measurement	Resolution of speed measurement
Incremental encoder, single track		no	$R_\varphi = \frac{2\pi}{I}$	$R_\omega = \frac{R_\varphi}{T}$
Incremental encoder, two tracks with pulse quadruplication		yes	$R_\varphi = \frac{2\pi}{4 \cdot I}$	$R_\omega = \frac{R_\varphi}{T}$
Sinus-Cosine-Encoder		yes	$R_\varphi = \frac{2\pi}{2^B \cdot I}$	$R_\omega = \frac{R_\varphi}{T}$
Resolver		yes	$R_\varphi = \frac{2\pi}{2^B \cdot p}$	$R_\omega = \frac{R_\varphi}{T}$
R_φ: Smallest measurable position change R_ω: Smallest measurable speed I: Pulses or periods per track and per revolution of the encoder			T: Measuring duration of the encoder electronics B: Bit number of the used analogue/digital converter p: Polpair number of the resolver	

Table 58 Resolution of motor encoders

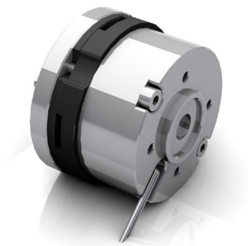
5.3.4 Encoder and brakes from Dunkermotoren

5.3.4.1 Encoder - Series RE / ME / AE / TG / R

Brushless motors series BG and brush-type DC motors series GR/G can be fitted with encoders. There is a wide range of optical and magnetic incremental encoders, absolute encoders, resolvers and tacho generators available. In some cases, encoders are already integrated into the motors. Combinations of encoders and brakes are possible. Depending on the motor-encoder combination, classes of protection up to IP 65 are possible.

5.3.4.2 Brakes - Series E

Brushless motors series BG and brushed DC motors series GR/G can be fitted with brakes. The standard offer is power-off brakes – means the brake is activated if no voltage is applied and no current flows. Power-on brakes are available on request. IP 54 covers are available for all brakes. Depending on the motor-brake combination, classes of protection up to IP 65 are possible.



5.4 Example: Pump motor

The following steady-state load data were determined for the pump motor in chapter 4.4:
• Motor torque M_M: 0.1 nM • Motor speed nM: 2600 rpm
Using these characteristic values a motor can be selected from the following motor list.

Data/ Technische Daten		BG 42x15		BG 42x30	
Nominal voltage/ Nennspannung	VDC	12	24	12	24
Nominal current/ Nennstrom	A*)	4.4	2.24	6.8	3.3
Nominal torque/ Nennmoment	Ncm*)	10.6	10.8	17.3	17.2
Nominal speed/ Nenndrehzahl	rpm*)	3410	3630	3330	3580
Friction torque/ Reibungsmoment	Ncm*)	1.1	1.1	1.8	1.7
Stall torque/ Anhaltemoment	Ncm**)	60.2	74.6	102	152
No load speed/ Leerlaufdrehzahl	rpm*)	4340	4390	4190	4110
Nominal output power/ Dauerabgabeleistung	W*)	38	41	60.6	64
Maximum output power/ Maximale Abgabeleistung	W	67.3	86	102	156
Torque constant/ Drehmomentkonstante	Ncm A-1**)	2.8	5.5	2.9	5.9
Peak current/ Zulässiger Spitzenstrom	A**)	26	15	40	22
Rotor inertia/ Rotor Trägheitsmoment	gcm²	24	24	44	44
Weight of motor/ Motorgewicht	kg	0.36	0.36	0.47	0.47

Figure 10 Extract from a catalogue for brushless DC motors with integrated power electronics

The following applies:	$M < M_N$ $n < n_N$	$0{,}1\ Nm < 0{,}106\ Nm$ $2600\ 1/min < 3610\ 1/min$

At the integrated power electronics, the voltage setpoint has to be adjusted so that the required speed of 2600 rpm is reached, but not exceeded.

5.5 Example: Door motor

The following characteristic values for selecting the motor have been determined in chapter 4.5: • Maximum motor torque for preselecting the motor M_{MVmax}: 0,167 Nm • Maximum speed of the motor n_{Mmax}: 1910 1/min.
Using these characteristic values a motor can be selected from the following motor list.

Data/ Technische Daten		GR 63x25			
Nominal voltage/ Nennspannung	VDC	12	24	40	60
Nominal current/ Nennstrom	A*)	5.2	2.7	1.7	1.1
Nominal torque/ Nennmoment	Ncm*)	13.7	14	13.3	14.5
Nominal speed/ Nenndrehzahl	rpm*)	3100	3300	3500	3300
Friction torque/ Reibungsmoment	Ncm*)	1.5	1.5	1.5	1.5
Stall torque/ Anhaltemoment	Ncm**)	82	108	118	116
No load speed/ Leerlaufdrehzahl	rpm*)	3600	3600	3800	3600
Nominal output power/ Dauerabgabeleistung	W*)	44.5	48.4	48.7	50

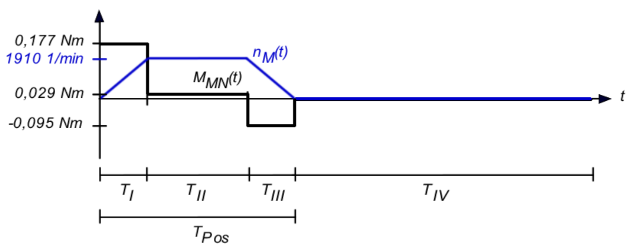
Maximum output power/ Maximale Abgabeleistung	W	77.3	101.8	117.4	119.3
Torque constant/ Drehmomentkonstante	Ncm A^{-1} **)	3	6	9.8	15.3
Terminal Resistance/ Anschlusswiderstand	Ω	0.44	1.33	3.33	7.89
Terminal inductance/ Anschlussinduktivität	mH	1	2.9	7.3	17.4
Starting current/ Anlaufstrom	A **)	27	18	12	7.6
No load current/ Leerlaufstrom	A **)	0.6	0.36	0.21	0.14
Demagnetisation current/ Entmagnetisierungsstrom	A **)	50	24	16	9.5
Rotor inertia/ Rotor Trägheitsmoment	gcm^2	400	400	400	400
Weight of motor/ Motorgewicht	kg	1.2	1.2	1.2	1.2

*) $\Delta\vartheta_w$ = 100 K; **) ϑ_R = 20°C ***) *at nominal point*/ im Nennpunkt

Figure 11 Extract from a catalogue for brushed DC motors

According to the requirements in chapter 2.5 a supply voltage of 24 V DC is available. Therefore the motor with the following characteristics is selected for the further calculations: • Rated torque M_N: 0,14 Nm • Maximum torque M_{max}: 101,8 W /(2π · 3300 1/min) = 0,29 Nm Rated speed n_N: 3300 1/min • Moment of inertia J: 4,0 · 10^{-5} kgm². In the motor recalculation the influence of the moment of inertia of the motor during the acceleration and deceleration is taken into account. Therefore the results in Table 47 are used.

Motion variables at the motor shaft



Segment I, acceleration	
Torque motor	$M_{MN} = J \cdot \alpha_1 + M_1 = 4{,}0 \cdot 10^{-5}\ kgm^2 \cdot 250 \frac{1}{s^2} + 0{,}167\ Nm = 0{,}177\ Nm$
Segment III, deceleration	
Torque motor	$M_{MN} = J \cdot (-\alpha_{max1}) + M_1 = 4{,}0 \cdot 10^{-5}\ kgm^2 \cdot \left(-250 \frac{1}{s^2}\right) - 0{,}085\ Nm = -0{,}095\ Nm$
RMS value of the torque	
RMS value of the torque driving side	$M_{eff} = \sqrt{\frac{(0{,}177\ Nm)^2 \cdot 0{,}8s + (0{,}0018\ Nm)^2 \cdot 1{,}7s + (-0{,}095\ Nm)^2 \cdot 0{,}8s}{8{,}3\ s}} = 0{,}062\ Nm$

Table 59 Motion variables at the motor shaft for a door motor

The following applies:	$M_{eff} < M_N$	$0{,}062\ Nm < 0{,}14\ Nm$
	$M_{MNmax} < M_{max}$	$0{,}177\ Nm < 0{,}29\ Nm$
	$n_{max} < n_N$	$1910\ 1/min < 3300\ 1/min$

All motion variables are within the permissible range. The preselected motor is suitable and can be used.

Since the door motor is a positioning application, the motor must be equipped with a position encoder. An incremental encoder with 2 tracks (pulse quadrupling) and 1024 pulses/revolution is selected.

The resolution of the linear motion at the wire rope is thus:

$$R_\varphi = \frac{2\pi \cdot d_U}{4 \cdot I \cdot i \cdot 2} = \frac{2\pi \cdot 0{,}06\ m}{4 \cdot 1024 \cdot 15 \cdot 2} = 0{,}003\ mm$$

I: Pulses or periods per track and per revolution of the encoder
i: Gear ratio
d_U: Diameter of the deflection pulleys at the driven side of the gearbox

The resolution of the linear motion of the door is thus sufficient.

Data/ Technische Daten		RE 22-2	RE 20S-2-100	RE 30-2	RE 30-2 TI	RE 30-3	RE 30-3 TI	RE 56-3	RE 56-3 TI	MR integ.
Operating voltage/ Versorgungsspannung	VDC	5	5	5	5	5	5	5	5	internal
Impulses per revolution/ Impulszahl pro Umdrehung	ppr	256	-	100 / 500 / 1024	1024	100 / 500	100 / 500	1000 / 2000	1000 / 2000	1024
Channels/ Kanäle	-	2	2	2	2	2 + Index	2 + Index	2+Index	2+Index	2+Index
Signal rise time/ Signalanstiegszeit	ns	500	-	200	14	180	14	7.5	180	-
Signal delay time/ Signalabfallzeit	ns*)	100	30	50	14	49	7.5	30	14	-
Current consumption/ Stromaufnahme	mA	max. 18	max. 20	17 (max. 40)	57 (max. 85)	57 (max. 80)	max. 85	57 (max. 85)	max. 85	internal
Output voltage/ Ausgangs-spannung (low-lewel)	VDC	max 0.4 (8.0 mA)	max 0.4	max. 0.4 (3.2 mA)	max. 0.5 (mA)	max. 0.4 (3.9 mA)	max. 0.4 (3.9 mA)	max. 0.4 (3.9 mA)	max. 0.5 (20 mA)	internal
Output voltage/ Ausgangs-spannung (high-lewel)	VDC	min. 2.4 (0.4 mA)	min. 0.1	min. 2.4 (40 µA)	min. 2.5 (mA)	min. 2.4 (200 µA)	min. 2.5 (200 µA)	min. 2.4 (200 µA)	min. 2.5 (200 µA)	internal
Max. output current/ Max. Ausgangsstrom	mA	-	20	-	20	-	20	-	20	internal
Operating temperature/ Betriebstemperatur	°C	-20...+85	0...+70	-40...+100	0...+70	-40...+100	0...+70	-40...+100	0...+70	-
Protection class/ Schutzart	IP	30	30	30	30	30	30	30	30	-

Figure 12 Extract from a catalogue for motor encoders

A brake is not required for the door motor.

6 Selection of the control unit

6.1 Characteristics and selection of the control unit

If the motion sequence at the motor shaft is determined and a specific motor is chosen, the appropriate control unit can be selected for variable speed motors and servo motors. The control unit has to be selected so that it fits functionally to the motor type and its output voltage corresponds to the rated voltage of the motor.

For the design of the control unit, the current requirement of the motor during the load cycle has to be determined. Depending on the motor type of different equations are needed to calculate current demand at the output of the control unit.

Motor type	Equations for determining the current of the control unit
Permanent magnet DC motor	$I = \left\lvert \frac{M_M}{k_T} \right\rvert$
Brushless DC motor	$I = \left\lvert \frac{M_M}{k_T} \right\rvert$
Synchronous motor	$I = \left\lvert \frac{M_M}{k_T} \right\rvert$
Asynchronous motor	$I = \sqrt{{I_0}^2 + \frac{M_M}{k_T}({I_N}^2 - {I_0}^2)}$
I: Output current of the control unit M_M: Torque of the connected motor k_T: Torque constant of the connected motor	I_0: No-load current of the connected asynchronous motor I_N: Rated current of the connected asynchronous motor

Table 60 Conversion of the motor torque to the output current of the control unit

The energy conversion in the control unit is subject to loss, which leads to rising temperature within the control unit. When the control unit is loaded, its temperature increases with a time delay. The time delay is determined by the thermal time constant of the control unit, which is generally in the range of a few seconds to minutes.

Since control units for variable speed motors and servo motors have a time-varying current, this must be converted to a continuous equivalent current, that heats the control unit in the same way as the current of the real load cycle. The continuous equivalent current is described by the RMS value of the current.

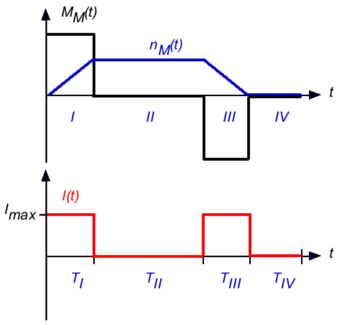
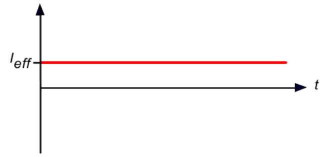
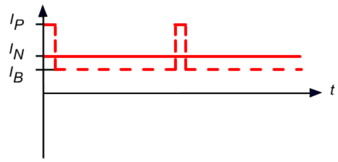
Load cycle	**Continuous equivalent current causing same heating**
	 **Permanent and peak current characteristics of the control unit** 
I_{eff}: RMS value of the current, general definition	$I_{eff} = \sqrt{\frac{1}{T}\int_0^T I^2 dt}$
I_{eff}: RMS value of the current, simplified formula for segment wise constant current	$I_{eff} = \sqrt{\frac{I_I{}^2 \cdot T_I + T_{II}{}^2 \cdot t_{II} + I_{III}{}^2 \cdot T_{III} + \cdots}{T_I + T_{II} + T_{III} + \cdots}}$
Selection condition	$I_{max} \leq I_P$ $I_{eff} \leq I_N$
M_M: Motor torque n_M: Motor speed (1/s) I: Output current of the control unit I_{max}: Maximum current during load cycle I_P: Peak current of the control unit	I_N: Rated current of the control unit I_B: Base current of the control unit $I_{I, II, III, IV}$: Current of the control unit within segment I, II, III, IV $T_{I, II, III, IV}$: Duration of segment I, II, III, IV T: Duration of load cycle

Table 61 Selection of the control unit according to peak and permanent current

In many control units the conversion from AC to DC at the input stage is carried out by a simple diode based rectifier. It is not able to feed back energy into the AC grid. Therefore the energy generated during deceleration must be converted into heat in a braking unit with a braking resistor connected.

The determination of a suitable braking unit and a suitable braking resistor is therefore a necessary additional selection step for the control unit.

The regenerative power that occurs in variable speed motors and servo motors must be converted into an average power. The average power heats the braking unit and braking resistor in the same way as the braking power of real load cycle.

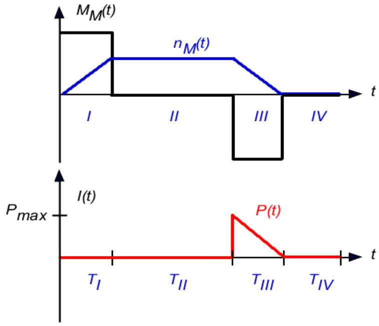
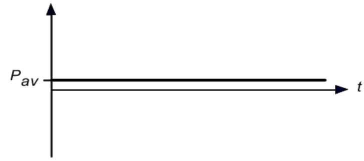
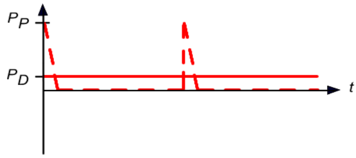
<table>
<tr><th>Load cycle</th><th>Continuous equivalent current causing same heating</th></tr>
<tr><td rowspan="3">
</td><td>
</td></tr>
<tr><td>Permanent and peak current characteristics of the control unit</td></tr>
<tr><td>
</td></tr>
<tr><td>P: Regenerative power Boundary condition: $M_M \cdot 2\pi \cdot n_M < 0$</td><td>$P = |M_M \cdot 2\pi \cdot n_M|$</td></tr>
<tr><td>Pav: Average regenerative power, general definition</td><td>$P_{av} = \frac{1}{T}\int_0^T P dt$</td></tr>
<tr><td>Pav: Average regenerative, simplified formula for ramp shaped course of the regenerative power</td><td>$P_{av} = \frac{\frac{1}{2} P_{max} \cdot T_{III}}{T_I + T_{II} + T_{III} + \cdots}$</td></tr>
<tr><td>Selection condition</td><td>$P_{max} \leq P_P$
$P_{av} \leq P_D$</td></tr>
<tr><td>M_M: Motor torque
n_M: Motor speed (1/s)
P_{max}: Maximum regenerative power during load cycle
P_P: Peak power of the braking unit and the braking resistor</td><td>P_D: Permanent power of the braking unit and the braking resistor
$T_{I, II, III, IV}$: Duration of segment I, II, III, IV
T: Duration of load cycle</td></tr>
</table>

Table 62 Selection of the control unit according to peak- and permanent power of the braking unit and the braking resistor

6.2 Integrated and external control units from Dunkermotoren

6.2.1 Controllers - Series BGE/ DME

The controllers are available for DC or AC supply and have been specially designed for optimum regulation of the speed, torque, and position of our dynamic motors. Please also consider the wide range of integrated controllers Dunkermotoren offers for brushless DC and linear range.

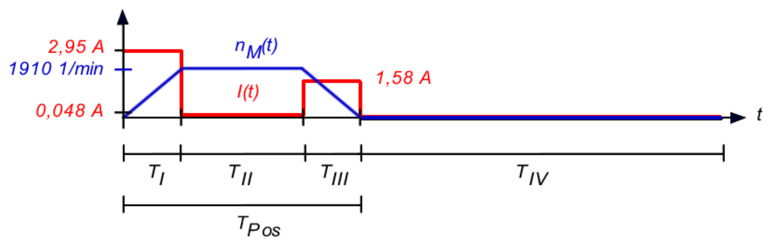
6.2.2 Motion control 4.0

The smart motors (series BG) of Dunkermotoren with integrated controller and field bus or industrial Ethernet interfaces will perfectly embed into your smart factory machinery and help you to increase productivity and efficiency. Dunkermotoren's solutions are notable for easy integration into customers systems.

Motors carry out tasks autonomously • Condition Monitoring and Predictive Maintenance • Motors communicate with other devices and with control/ SCADA level • Reduced cabling effort, protection against dust and humidity • Innovative and energy saving DC concepts

6.3 Example: Door motor

In chapter 5.5, a motor for a door drive with the following characteristics was selected:
• Torque constant k_T: 0.06 Nm/A
Using this characteristic value the current demand of the motor can be determined.

Current demand of the motor	
	
Segment I, acceleration	
Motor current	$I = \frac{M_M}{k_T} = \frac{0{,}177\ Nm}{0{,}06\ \frac{Nm}{A}} = 2{,}95\ A$
Segment II, constant speed	
Motor current	$I = \frac{M_M}{k_T} = \frac{0{,}0029\ \ Nm}{0{,}06\ \frac{Nm}{A}} = 0{,}048\ A$
Segment III, deceleration	
Motor current	$I = \frac{M_M}{k_T} = \frac{\lvert -0{,}095\ Nm \rvert}{0{,}06\ \frac{Nm}{A}} = 1{,}58\ A$

Segment IV, pause	
Motor current	$$I = \frac{M_M}{k_T} = \frac{0\,Nm}{0{,}06\,\frac{Nm}{A}} = 0\,A$$
RMS value of the current	
RMS value of the current	$$I_{eff} = \sqrt{\frac{(2{,}95\,A)^2 \cdot 0{,}8s + (0{,}048\,A)^2 \cdot 1{,}7s + (1{,}58\,A)^2 \cdot 0{,}8s}{8{,}3\,s}} = 1{,}04\,A$$

Table 63 Current demand of the brushless DC motor for a door motor

Using these characteristic values a control unit can be selected from the following unit list.

Data/ Technische Daten		BGE 6010 A	BGE 6015 A
		external/ extern	*external*/ extern
Master functionality (MPU integrated)/ Masterfunktionalität (MPU integriert)	-	*yes*/ ja	*yes*/ ja
Nominal voltage electronic supply/ Versorgungsspannung Elektronik	VDC	9 ... 30	9 ... 30
Nominal voltage power supply/ Versorgungsspannung Leistung	VDC	9 ... 60	9 ... 60
Current consumption/ Stromaufnahme	mA	typ. 60 @ 24 V	typ. 60 @ 24 V
Peak output current/ Maximaler Ausgangsstrom	A	50	50
Continuous output current/ Zulässiger Dauerausgangsstrom	A	10* (@ 48 V)	15* (@ 48 V)
Digital input/ Digitale Eingänge	-	8	8
Digital output/ Digitale Ausgänge	-	2	2
Analog input/ Analoge Eingänge	-	2 (-10 ... +10 V)	2 (-10 ... +10 V)
Protection class/ Schutzart	IP	20	20
Ambient temperature/ Umgebungstemperatur	°C	0 ... +70	0 ... +70
Rel. humidity/ Umgebungsfeuchtigkeit	%	5 ... 85	5 ... 85
Weight/ Gewicht	kg	0.31	0.31

* 40°C 32 kHz PWM

Figure 13 Extract from a catalogue for control units

The following applies:	$I_{eff} < I_N$ $I_{Mmax} < I_{max}$	$1{,}04\,A < 10\,A$ $2{,}95\,A < 50\,A$

All characteristic values are within the permissible range. The selected control unit is suitable and can be used.

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List of abbreviations

AC	Alternating current
DC	Direct current
EC	Electronically commutated
EMK	Electromotive Force
IP	International Protection

List of used symbols

Naming	Symbol	Unit
Angular acceleration	α	$1/s^2$
Angular acceleration at driving side of the gearbox	α^1	$1/s^2$
Angular acceleration at driven side of the gearbox	α^2	$1/s^2$
Maximum angular acceleration allowed during a positioning process	α_{max}	$1/s^2$
Maximum permissible angular acceleration allowed during a positioning process	αP	$1/s^2$
Angle	β	
Pressure difference of a plant	Δp_A	N/m^2
Pressure difference at operating point	Δp_{OP}	N/m^2
Pressure difference of a fan	Δp_L	N/m^2

Naming	Symbol	Unit
Pressure difference of a pump	Δp_P	N/m^2
Efficiency	η	
Viscosity	η	Nms
Angle	φ	
Angle at driving side of the gearbox	φ_1	
Angle at driven side of the gearbox	φ_2	
Position setpoint for angle	φ_{Pos}	
Switching ratio	λ	
Sliding friction coefficient	μ_G	
Static friction coefficient	μ_H	
Angular jerk	ρ	$1/s^3$
Density	ρ	kg/m^3
Temperature	υ	K
Ambient temperature	υ_0	K
Motor temperature	υ_M	K
Over temperature	υ_{Ov}	K
Final steady-state temperature	υ_{St}	K
Angular speed	ω	$1/s$
Angular speed at driving side of the gearbox	ω_1	$1/s$
Angular speed at driven side of the gearbox	ω_2	$1/s$
Maximum angular speed during a positioning process	ω_{max}	$1/s$
Maximum permissible angular speed during a positioning process	ω_P	$1/s$
Acceleration	a	m/s^2
Length values	a, b	m
Maximum permissible acceleration allowed during a positioning process	a_P	m/s^2
Maximum acceleration allowed during a positioning process	a_{max}	m/s^2
Number of bits	B	

Naming	Symbol	Unit
Rolling friction coefficient	c_R	
Drag coefficient	c_W	
Diameter	d	m
Outer diameter	d_a	m
Inner diameter	d_i	m
Diameter of a wheel	d_R	m
Diameter of a support roll	d_S	m
Diameter of a pulley	d_U	m
Force	F	$N = kgm/s^2$
Force of the force compensation	F_A	$N = kgm/s^2$
Acceleration force	F_B	$N = kgm/s^2$
Weight force	F_G	$N = kgm/s^2$
Force of the weight compensation	F_{GA}	$N = kgm/s^2$
Downhill slope force	F_H	$N = kgm/s^2$
Load force	F_L	$N = kgm/s^2$
Rated frequency	f_N	$Hz = 1/s$
Friction force	F_R	$N = kgm/s^2$
Sliding friction force	F_{Rg}	$N = kgm/s^2$
Static friction force	F_{Rh}	$N = kgm/s^2$
Rolling resistance force	F_{Rr}	$N = kgm/s^2$
Flow resistance force	F_{St}	$N = kgm/s^2$
Traction force	F_Z	$N = kgm/s^2$
Acceleration due to gravity (9.81 m/s^2)	g	m/s^2
Discharge head of the pump	H	m
Gear ratio	i	
Electrical current	I	A
Pulses or periods per track and per revolution	I	
No-load current	I_0	A
Armature current	I_A	A

Naming	Symbol	Unit
Start-up current	$I_{Start\text{-}up}$	A
Base current	I_B	A
RMS value of the current	I_{eff}	A
Current within segment I, II, III, IV	$I_I, I_{II}, I_{III}, I_{IV}$	A
Maximum gear ratio	i_{max}	
Maximum current	I_{max}	A
Minimum current	I_{min}	A
Rated current	I_N	A
Optimum gear ratio	i_{opt}	
Maximum permissible current	I_P	A
Stator current	I_S	A
Jerk	j	m/s^3
Moment of inertia	J	kgm^2
Sum of moments of inertia at driving side of the gearbox	J_1	kgm^2
Sum of moments of inertia at driven side of the gearbox	J_2	kgm^2
Moment of inertia of the motor	J_M	kgm^2
Moment of inertia, in which the axis of rotation passes through the centre of gravity	J_S	kgm^2
Moment of inertia of the support roll	J_S	kgm^2
Moment of inertia of the rope drum	J_T	kgm^2
Moment of inertia of a pulley	J_U	kgm^2
Torque constant	k_T	Nm/A
Length	l	m
Length segment 1, 2	l_1, l_2	m
Mass	m	kg
Torque	M	$Nm = kgm^2/s^2$
Standstill torque	M_0	$Nm = kgm^2/s^2$
Torque at driving side of the gearbox	M_1	$Nm = kgm^2/s^2$
Torque at driven side of the gearbox	M_2	$Nm = kgm^2/s^2$

Naming	Symbol	Unit
RMS value of the torque at driven side of the gearbox	M_{2eff}	Nm
Torque at driven side of the gearbox within segment I, II, III or VI	$M_2I, M_{2II}, M_{2III}, M_{2IV}$	Nm
Acceleration torque	M_B	$Nm = kgm^2/s^2$
RMS value of the torque	M_{eff}	Nm
Mass of the belt	m_G	kg
Mass of a counterweight	m_{GA}	kg
Stall torque	M_K	$Nm = kgm^2/s^2$
Masse of the load	m_L	kg
Load torque	M_L	$Nm = kgm^2/s^2$
Motor torque	M_M	$Nm = kgm^2/s^2$
Maximum permissible torque	M_{max}	$Nm = kgm^2/s^2$
Minimum permissible torque	M_{min}	$Nm = kgm^2/s^2$
Motor torque motor recalculation	M_{MN}	$Nm = kgm^2/s^2$
Motor torque motor preselection	M_{MV}	$Nm = kgm^2/s^2$
Rated torque	M_N	Nm
Point mass	m_P	kg
Friction torque	M_R	$Nm = kgm^2/s^2$
Mass of the support roll	m_S	kg
Mass of the wire rope or belt	m_{SZ}	kg
Mass of the pulley	m_U	kg
Speed	n	$1/min$
No-load speed	n_0	$1/min$
Speed at driving side of the gearbox	n_1	$1/min$
Mean absolute speed at driving side of the gearbox	n_{1av}	$1/min$
Maximum permissible speed at driving side of the gearbox	n_{1max}	$1/min$
Rated speed of the gearbox	n_{1N}	$1/min$
Speed at driven side of the gearbox	n_2	$1/min$
Speed at operating point	n_{AP}	$1/min$

Naming	Symbol	Unit
Mean absolute speed	n_{av}	$1/min$
Number of fixed deflection pulleys	n_F	
Number of movable deflection pulleys	n_L	
Motor speed	n_M	$1/min$
Maximum permissible speed	n_{max}	$1/min$
Rated speed	n_N	$1/min$
Number of wheels	n_R	
Number of support rolls	n_S	
Pressure	p	N/m^2
Polpair number	p	
Power		
Pressure at the inlet of the pump or the fan	P	$W = VA = Nm/s$
Power at driving side of the gearbox	p_1	N/m^2
Pressure at the outlet of the pump or the fan	P_1	$W = VA = Nm/s$
Mean absolute power	p_2	N/m^2
Permanent power	P_{av}	$W = VA = Nm/s$
Electrical power, active power	P_D	$W = VA = Nm/s$
Maximum power	P_{el}	$W = VA = Nm/s$
Mechanical power	P_{max}	$W = VA = Nm/s$
Rated power	P_{mech}	$W = VA = Nm/s$
Maximum permissible power	P_N	$W = VA = Nm/s$
Conveying capacity of the pump	P_P	$W = VA = Nm/s$
Power dissipation	P_P	$W = VA = Nm/s$
Volume flow	P_{Loss}	$W = VA = Nm/s$
Volume flow at operating point	Q	m^3/s
Volume flow of a pump	Q_{OP}	m^3/s
Radius	r	m
Resolution of the angle	$R\phi$	
Resolution of the angular speed	R_ω	$1/s$

Naming	Symbol	Unit
Armature resistance	R_A	$\Omega = V/A$
Sum of series resistors	$R_{V\Sigma}$	$\Omega = V/A$
Series resistance 1 or 2	R_{V1}, R_{V2}	$\Omega = V/A$
Distance	s	m
Slip	s	
Stall slip	s_K	
Position setpoint for distance	s_{Pos}	m
Time	t	s
Time within the segment I, II, III or VI	$t_I, t_{II}, t_{III}, t_{VI}$	s
Duration of the segment I, II III or VI	$T_I, T_{II}, T_{III}, T_{VI}$	s
Duration of the entire positioning process	T_{Pos}	s
Thermal time constant	T_{th}	s
Electrical voltage	U	V
Armature voltage	U_A	V
Motor voltage	U_M	V
Grid voltage	U_N	V
Velocity	v	m/s
Maximum permissible velocity during positioning process	v_P	m/s
Maximum velocity during positioning process	v_{max}	m/s
Number of switching stages	z	
Number of supporting ropes of the hoist	z	

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