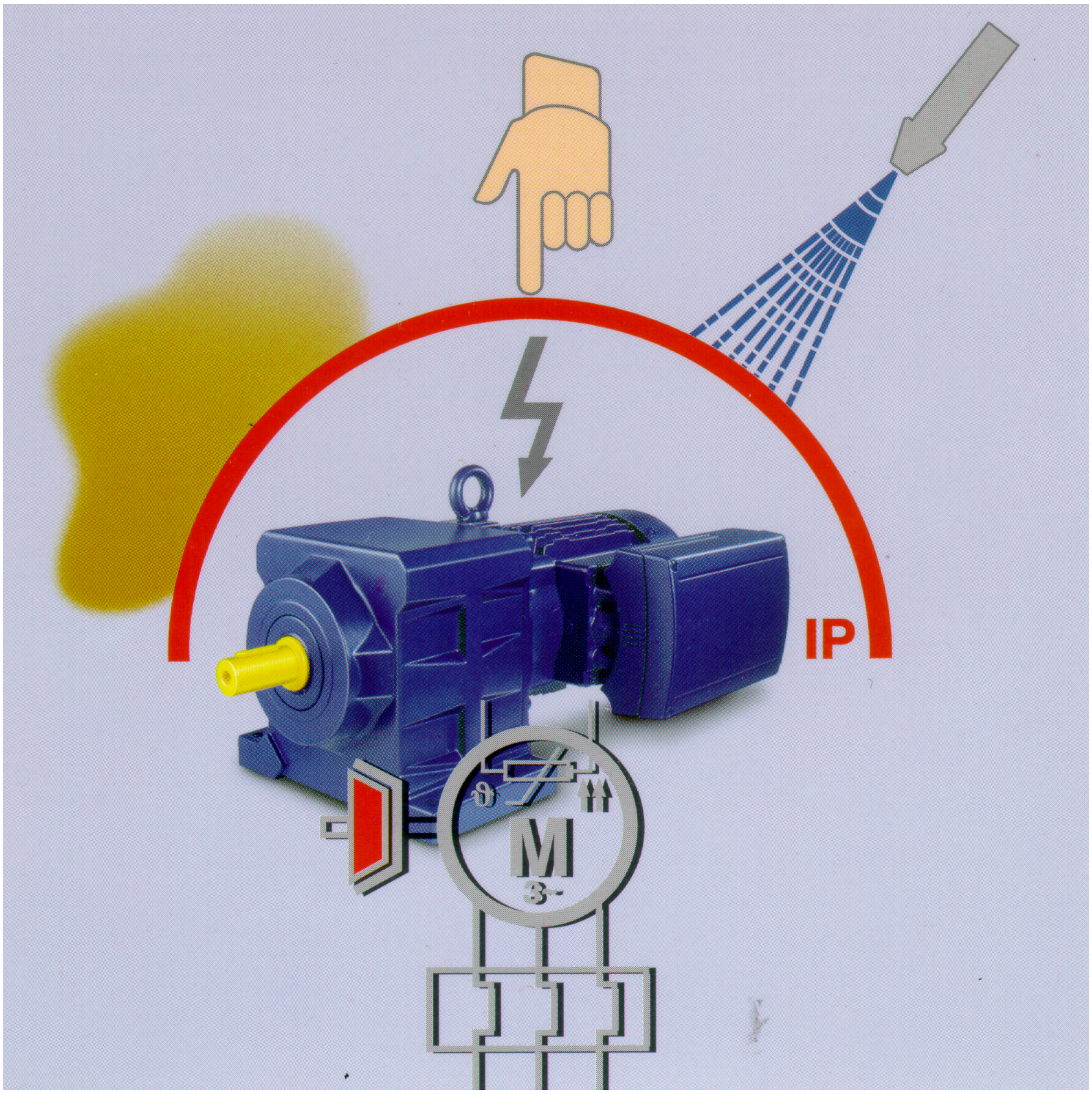
Protective measures for three-phase geared motors

Protection against access, environmental influences, electrical and mechanical overloading



BAUER geared motors

VLT® frequency converters

Helmut Greiner

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Dipt.-Ing. (FH) Helmut Greiner (born 1929) began his electrotechnical practice in 1945 when he commenced an apprenticeship with an electrical contractor. After his studies he worked for 40 years with Bauer Antriebstechnik in Esslingen in the field of research and development of electrical motors and power transmission engineering. He is now acting as a consultant for Danfoss Bauer.

Preface

Protective measures for three-phase geared motors

Protection against access, environmental influences, electrical and mechanical overloading

Three-phase cage motors are the number one choice in electric drive technology. They are robust and require little maintenance. A static frequency inverter allows their speed to be adjusted or controlled, which is why this type of motor is increasingly encroaching into fields of application previously reserved for D.C. shunt motors.
On the back of consistent ongoing development of the “individual drive”, electric motors are not only being exposed increasingly to natural and work-related environmental influences, they are also being required to take on more and more tasks previously solved by mechanical means: operating in switching mode and inching, actuating and regulating and much more besides.
Particular consideration must be given to the “protection of the drive motor” at the planning, installation and operating stages to minimize production downtimes and repair costs.

The environmental influences acting on electrical machines may vary greatly at the site of installation. The selection of the correct IP degree of protection is an important factor, but not sufficient on its own. Terms such as “condensation”, “outdoor installation” and “tropic-proof” give an idea of the various requirements.

Increased current drawn in many cases of overloading, such as mechanical overload, overvoltage, undervoltage, frequent switching, locking, single-phasing, leads to abnormal heating of the winding. However, there are other instances where the winding carries the normal rated current but can still be at risk. These occur when the ambient temperature rises excessively, the flow of cooling air is restricted or where an inverter-fed motor is operating at low frequency. The type of hazard and the degree of protection desired will determine which of the various methods of protecting the motor windings should be selected. In certain applications it may even be necessary to use a combination of two different protective devices.

Unlike thermal overloading of the motor winding, surprisingly short-time and abrupt torque peaks are often all it takes to overload the mechanical power transmission component (shafts, bearings, couplings, transmission). Due to dynamic processes, these peak values may be well in excess of the maximum moments developed by the motor. This type of overloading cannot be detected by electrical means and so demands that special precautions be taken in the planning and selection of power transmission components.

This book reflects many years of practical experience – it is aimed at all those working in the field of drive technology.

Aichschieß, July 2002

Helmut Greiner

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1 Three-phase motors and geared motors in the field of drive technology

Three-phase asynchronous cage motors are the number one choice in electric drive technology. They owe their good reputation to their robust construction and low maintenance requirement. The use of a static frequency inverter allows their speed to be adjusted or controlled, which is why this type of motor is increasingly encroaching into fields of application previously reserved for D.C. shunt motors. On the back of consistent ongoing development of the ***individual drive***, electric motors are not only being exposed increasingly to natural and work-related environmental influences, they are also being required to take on more and more tasks previously solved by mechanical means: operating in switching mode and inching, actuating and regulating are examples of the demands placed on electric motors. Particular consideration must be given to the protection of the drive motor at the planning, installation and operating stages to minimise production downtimes and repair costs.
The following two sections explain why this consideration is limited to three-phase motors but includes geared motors.

1.1 Numbers of three-phase motors

The three-phase asynchronous cage motor can be regarded as the ***industrial drive***.
About 70 % of all industrial drives are of this motor type (Fig. 1.1 and 1.2); about 25 million drives of this type are operating in Germany.

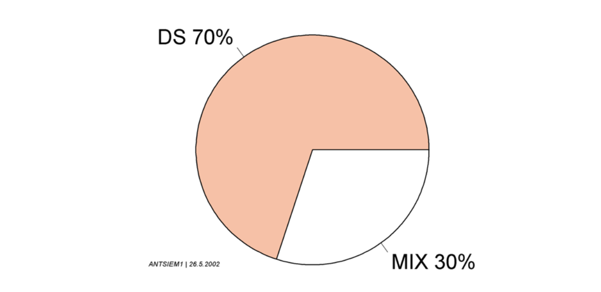


Fig. 1.1
Three-phase motors as a proportion of the industrial drives in Germany
DS Three-phase motors
MIX Other motor types

Source: SIEMENS

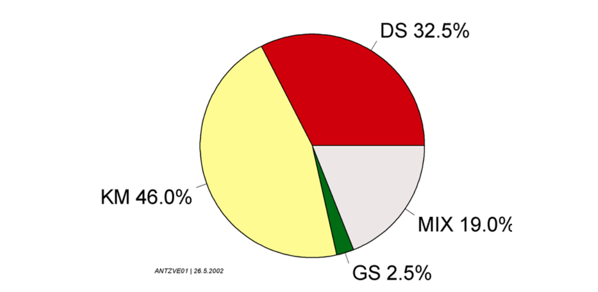


Fig. 1.2
Proportion of three-phase motor of the number of motors produced in Germany in 2001
DS Three-phase motors
GS D.C. motors
KM Small-power motors
MIX Other motor types
Source: ZVEI Annual Report 2001

The benefits of this type of drive cannot be ignored; they are unavoidably linked to the definition of output speed as given by:

$$\boldsymbol{n = \frac{60 \cdot f}{p} - \Delta n}$$

n	Full load speed in r/min
f	Supply frequency in Hz
p	Number of pole pairs (usually between 1 and 6)
Δn	Slip speed in r/min

Actual speeds vary according to the number of pole pairs and the slip (Table 1.1).

Table 1.1: Standard speeds from three-phase asynchronous motors

Number of poles	Synchronous speed in r/min		Rated speed in r/min	
	at 50 Hz	at 60 Hz	at 50 Hz	at 60 Hz
2	3000	3600	2750 to 2980	3200 to 3520
4	1500	1800	1300 to 1450	1600 to 1760
6	1000	1200	830 to 990	1020 to 1170
8	750	900	650 to 740	780 to 870
12	500	600	440 to 485	530 to 590

1.2 Proportion of geared motors

The speeds best suited to conventional electric motors from the point of view of technology and economy (e.g. 1500 r/min from a 4-pole three-phase asynchronous motor) are too high for the majority of industrial drive technology applications (Fig. 1.3). The inevitable reduction gearing is combined for convenience with the motor to form a single unit. Geared motors are generally more efficient, offer greater protection against accidents, require less space and are simpler to install than open or separate reduction transmissions. Because the gear unit not only reduces the speed but also increases the torque, unlike virtually all purely electric or electronic systems (such as D.C. motors or inverter-fed motors), geared motors are becoming increasingly popular in factories and workshops for installation and maintenance tasks.

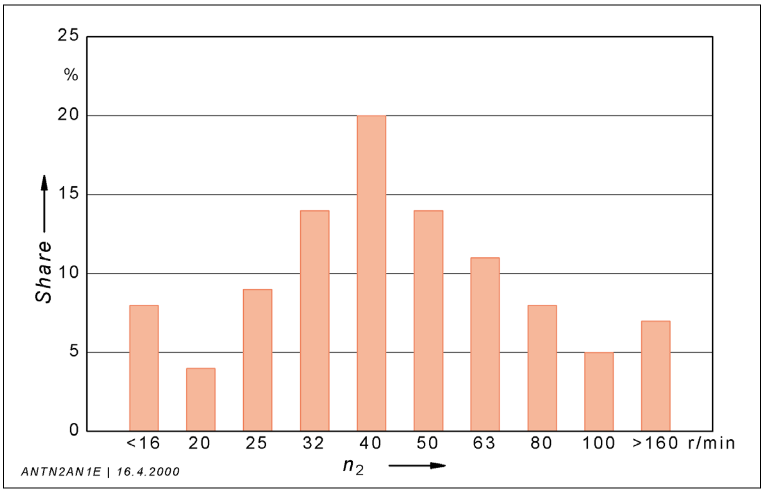


Fig. 1.3
Speed statistics illustrating the speed requirement in industrial drive technology [2.4]

The proportion of geared motors of the total of all electric drives in operation varies considerably from sector to sector. In large chemical plants, where hydraulic and pneumatic conveying dominates, the proportion is “only” about 15 to 30 %, whereas in the automotive industry, with its highly-rationalized conveying and handling systems, geared motors make up approximately 50 to 75 % of all drives in use and in stock (Fig. 1.4).

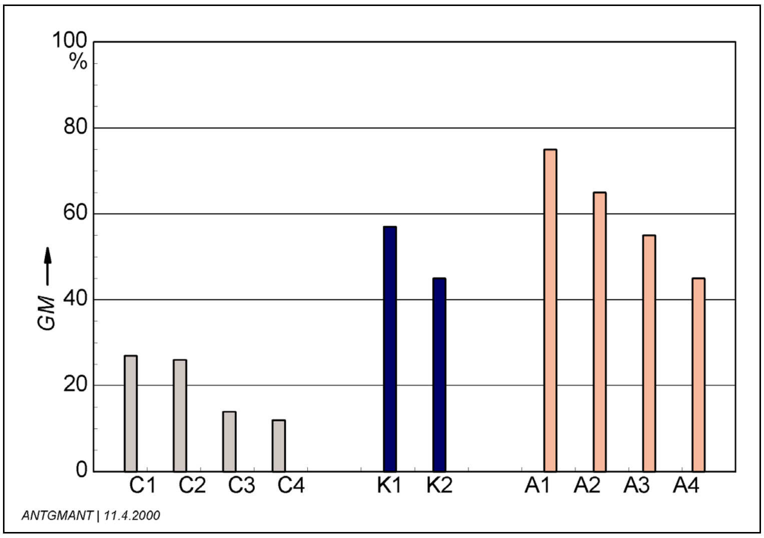


Fig. 1.4
Proportion of geared motors (GM) of the total number of electric drives in
automotive industry works (A1 to A4),
electricity utilities (including actuators) (K1, K2)
and
the chemicals industry (C1 to C4) [2.5]

2 Protection against access

Protection against access plays a major role in ***protection against electric shock*** [2.17].

2.1 Direct contact

In the case of rotating electrical machines, protection against direct contact is usually provided by an enclosure which prevents access to hazardous parts.
Although the IP Code has offered the option to implement the degree of protection against access by distances or guards – indicated by the suffix letters A, B, C or D – as of the new version of the standard, the degree of protection on rotating electrical machines has traditionally been achieved by limiting the opening widths. The same code numbers and methods of test are used for protection against ingress of foreign objects and access to hazardous parts.
Persons are to be protected against:

- ☐ access to live low-voltage parts (rated voltage ≤ AC 1000 V),
- ☐ access to hazardous mechanical parts (smooth rotating shafts are not considered hazardous),
- ☐ Approach below adequate clearance to hazardous high-voltage live parts inside an enclosure (rated voltage > AC 1000 V).

2.1.1 Hazardous live parts

Parts which could induce an electric shock (e.g. bare live terminals) must be enclosed or covered by an enclosure which is ***safe from finger-touch*** under normal circumstances, i.e. corresponds to degree of protection IP2X (optionally IPXXB; see section 3). The terminal box on rotating electrical machines is usually designed in accordance with degree of protection IP4X or IP5X at least, even in the case of open-circuit air-cooled machines.

2.1.2 Hazardous mechanical parts

The moving parts on rotating electrical machinery (e.g. the fan) must also be included in any consideration of protection against access.
In contrast to terminal boxes, the maximum permissible opening width must be exploited by the fan cowl to provide the air flow required for cooling.

The blades or spokes of fans external to the enclosure **(*external fans*)** must be protected against contact by means of a cowl (Fig. 2.1), complying with the requirements set out in Table 2.1.

Table 2.1.2.1 Cowl on external fans

Degree of protection of the machine	Fan cowl tested using
IP0X and IP1X	50 mm diameter sphere
IP2X to IP5X	Test finger

The rotor is slowly rotated by hand for the purposes of the test. Smooth rotating shafts and similar parts are not considered dangerous. In certain applications, such as agricultural or domestic appliances, more extensive precautions against accidental contact may be required. Under the "intended use" according to DIN 31000 / VDE 1000, “General principles for the safety design of technical products” the following degrees of protection against contact and hazard from moving parts are standard:

- ☐ IP0X for use in closed rooms for electrical operations (degree of protection IP 0X is not permissible for hazardous moving parts; these must be protected against unintentional contact),
- ☐ IP1X for use in rooms for electrical operations
- ☐ IP2X in all other cases.

Fig. 2.1.2.2
Fan cowl of a three-phase motor.
A 12 mm mesh size in accordance with degree of protection IP2X is sufficient on the inlet grille; however, a mesh size of 8 mm x 8 mm is usually provided

The standards or other technical codes of practice pertaining to certain applications contain more extensive requirements or specify the measures to be taken to prevent a particular type of hazard.
Installation regulations, such as standards in the DIN VDE 0100 series, specify the measures to be taken to prevent a particular type of hazard, for example by additional covers, spacers or guards, or the installation in an enclosure.

2.1.3 Child fingers

The principle that only ***instructed persons operate*** *industrial* machinery, such as electric motors, currently applies. Protection against access is therefore based on an adult's finger. Ventilation openings on an electric motor may, therefore, be slots or round/square holes up to a width of 12 mm. As an opening width of only 8 mm x 8 mm only was previously permissible for explosion-proof motors, most were designed uniformly with a mesh size of 8 mm (see Fig. 2.1.2.2). Motors with these types of fan cowls are increasingly to be found in ***lay applications*** such as the drives for high-pressure jets, hedge trimmers, concrete mixers. Fig. 2.1.3.1 shows that protection against ***intentional contact by children*** is not guaranteed by the standardised safety distances devised on the basis of an adult finger.

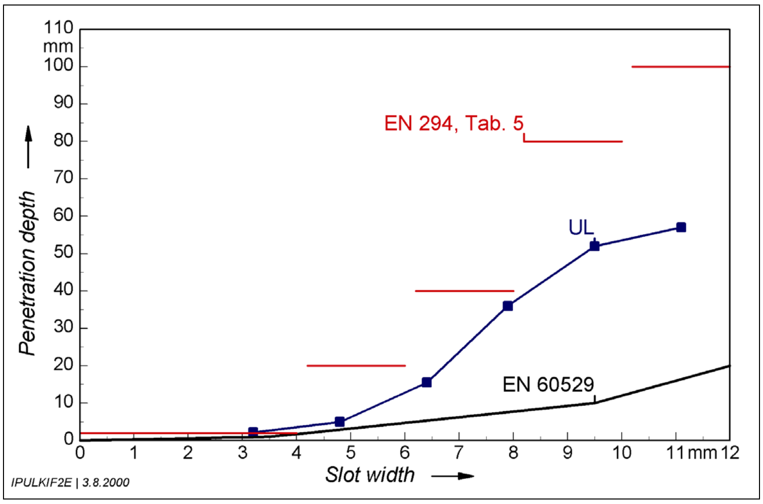


Fig. 2.1.3.1
Comparison of safety distances and penetration depths

EN 60529	Penetration depth of the test finger in accordance with EN 60529 / IEC 60529 for IP2X or IPXXB
EN 294, Table 5	Safety distances prescribed in EN 294 behind slot widths for persons aged 3 years and older
UL	Penetration depths (upper limit value) determined by tests carried out by “Underwriters Laboratories” using 100 children aged between 3 and 10 years

Reference is made in subclause 5.3 of the standard on the degree of protection of electrical machines (EN 60034-5 / IEC 60034-5)) to the external fan cowl in terms of the hazard posed to children:
In certain applications, such as agricultural or domestic appliances, more extensive precautions against accidental or deliberate contact may be required.
Fig. 2.1.3.2 shows how ***"more extensive precautions"*** may appear.

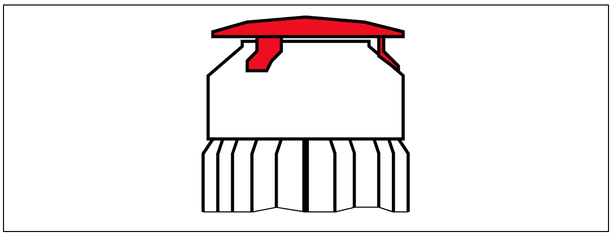


Fig. 2.1.3.2
Additional guard for increased protection against access to the fan cowl of a surface-ventilated closed electric motor

Work is currently underway in international standards committee TC 70 initiated by ACOS (the Advisory Committee on Safety) to determine the sizes of a standard child's test finger. Following appropriate expansion of the standards governing the electrical machinery affected, this will then be used to test the degree of protection offered against access by children.

Summary
The manufacturer must be informed of increased requirements on the degree of protection against access to the external fan of an electric motor beyond that of the standardized finger safety.
The responsibility to provide protection against access to the free shaft and transmission components fitted to it (couplings, belt pulleys, chainwheels) rests solely with the designer or installer of the machinery. This also applies where a second shaft extension is fitted to the fan side of the motor.

2.2 Indirect contact

2.2.1 Protective conductors

The majority of electrical machines adopt ***protective conductor protective measures*** to provide ***protection against electric shock under failure*** **or** ***fault protection***.
The design requirements on the earth terminal generally to be fitted inside the terminal box are specified in clause 30 of EN 60034-1 / IEC 60034-1 [1.6]:
Machines shall be provided with means for connecting a protective conductor or an earth conductor, such means being identifed by the appropriate symbol or legend. This requirement does not apply to machines with supplementary insulation, to machines with rated voltages up to and including 50 V A.C. or 120 V D.C. (See IEC 60364-4-41, Clause 411 and IEC 60449), or to machines for assembling in apparatus with supplementary insulation.
In the case of machines having rated voltages greater than 50 V A.C. or 120 V D.C., but not exceeding 1 000 V A.C. or 1 500 V D.C., the terminal for the earth conductor shall be situated in the vicinity of the terminals for the line conductors, being placed in the terminal box if one is provided. Machines having rated outputs in excess of 100 kW shall have, in addition, an earth terminal fitted on the frame.
Machines for rated voltages greater than 1 000 V A.C. or 1 500 V D.C. shall have an earth terminal on the frame, for example an iron strip, and in addition, a means inside the terminal box for connecting a conducting cable sheath, if any.
The earth terminal shall be designed to ensure a good connection with the earth conductor without any damage to the conductor or terminal. Accessible conducting parts which are not part of the operating circuit shall have a good electrically conducting connection with each other and with the earth terminal.
When all bearings and the rotor winding of a machine are insulated, the shaft shall be electrically connected to the earth terminal, unless the manufacturer and the purchaser agree to alternative means of protection.
When an earth terminal is provided in the terminal box, it shall be assumed that the earth conductor is made of the same metal as the live conductors.
When an earth terminal is provided on the frame, the earth conductor may, by agreement, be made of another metal (e.g. steel). In this case, in designing the terminal, proper consideration shall be given to the conductivity of the conductor.
The earth terminal shall be designed to accommodate an earth conductor of cross sectional area in accordance with Table 2.21. If an earth conductor larger than the size given in the table is used, it is recommended that it should correspond as nearly as possible to one of the other sizes listed.

Table 2.2.1
Cross-sections of earth conductors (extract for standard motors up to a shaft height of 280)

Current-carrying conductor (mm²)	4	6	10	16	25	35	50	70	95	120
Earth or protective conductor (mm²)	4	6	10	16	25	25	25	35	50	70

In the case of current-carrying conductors of other cross-sections, the minimum cross-section of the earth or protective conductor must be at least the same:
- as that of the current-carrying conductor for conductor cross-sections up to 25 mm^2
- 25 mm^2 for conductor cross-sections between 25 mm^2 and 50 mm^2
- 50 % of the cross-section of the current-carrying conductor for conductor cross-sections over 50 mm^2.

The earth terminal must be marked in accordance with EN 60445.

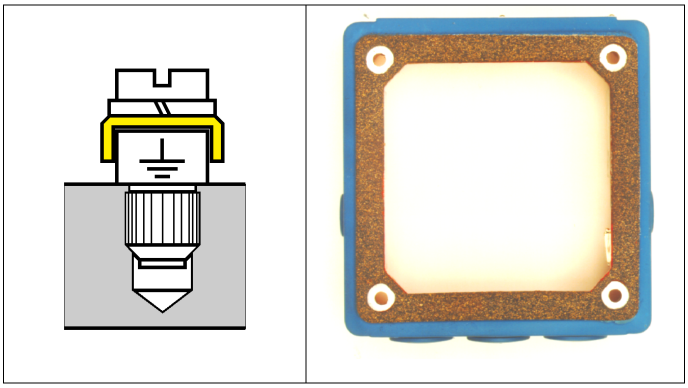


Fig. 2.2.2
Example of a protective conductor terminal (left)
and for the connection of the same conductivity between the terminal box and enclosure or cover (bright metal support cams on the aluminium die-cast part)

2.2.2 Equipotential bonding

Additional potential equalisation should bring the enclosure of the electrical machine and third-party conductive parts to the same or approximately the same potential. The manufacturer must fit an external protective conductor terminal (as shown in Fig. 2.2.2, for example) for the connection near the terminal box. This additional protective measure is required by the regulations accompanying certain applications – e.g. for installation in agricultural locations, in locations exposed to fire hazards or in explosive atmospheres [1.16], [1.17].
Motors which have been tested and approved for a specific type of protection (e.g. “e”, “d” or “p”) have this protective conductor terminal fitted at the works as part of the protection for use in explosive atmospheres. For other applications, this must be agreed on a case by case basis between the customer and manufacturer unless the rated output is higher than 100 kW (see section 2.2.1).

2.3 Converter-fed motors

If certain convertors (such as frequency inverters with a D.C. link in three-phase bridge connection) are used, ***non-pulsing D.C. fault currents*** could occur in the event of errors on the D.C. side. These could jeopardise the correct function of the residual current device. The VDE regulations are currently being expanded accordingly and universal current-sensitive residual current-operated circuit-breakers (type B) will be offered.
Full details on this topic are provided in [3.4], [3.5], [3.12], [3.13].

3 IP degrees of protection (IP Code)

When choosing an electrical machine, it is important that it meets the operating and environmental conditions. The selection of the correct ***degree of protection*** is an important factor, but not the only guarantee of trouble-free operation [2.1], [2.19].
The degree of protection provided by an enclosure is indicated by an alphanumeric code (***IP code***).
The following notes apply to the status specified in EN 60529 / IEC 60529 [1.1].

IP 2 3 C M

Code letters
(International Protection)

First **characteristic numeral**
(numerals 0 to 6, or letter X)

Second **characteristic numeral**
(numerals 0 to 8, or letter X)

Additional **letter** (optional)
(letters A, B, C, D)

Supplementary **letter** (optional)
(letters H, M, S, W)

3.1 Protection against access in the IP code

The first code number and the recently introduced additional letter are of most interest in terms of protection against access.
In principle, the ***protection against access to hazardous parts*** can be achieved and described by two methods:
- ***small opening widths*** in the enclosure which prevent the ingress of foreign object and test probes;
- large opening widths, or ***inner barriers*** *or* ***sufficient distances***, which prevent test probes of a limited length from accessing hazardous parts.

Protection against access is most commonly attained on electrical machines by ***limitation of the opening widths*** and can therefore be described by the first code number of an IP code comprising two numerals.
However, both methods are described here because other fields also make use of the “suffix letter” ***option*** and the standards for the protection against direct contact are expressed in safety regulations by the new IP Code (e.g. IPXXB).

3.1.1 Optional additional letter

Additional letters are only used
- if the actual protection against access to hazardous parts is greater than the protection specified by the first code number or
- if only the protection against access to hazardous parts is specified and the first code number is replaced with an X.

This higher degree of protection could be provided by guards, suitable shape of openings or distances inside the enclosure (Table 3.1.1).

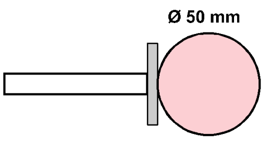
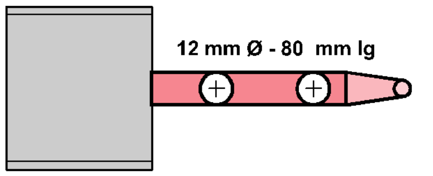
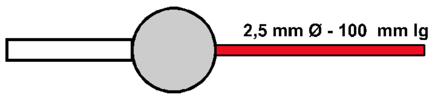
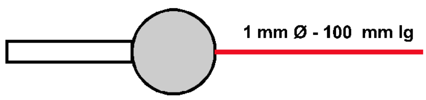
Table 3.1.1 Additional letter for the protection against access to hazardous parts

Suffix letter	Brief description of degree of protection	Definition
A	Protected against access with the back of the hand	The access probe (50 mm diameter sphere) shall have adequate clearance from hazardous parts.
B	Protected against access with a finger	The jointed test finger (12 mm diameter, 80 mm long) shall have adequate clearance from hazardous parts.
C	Protected against access with a tool	The access probe (2.5 mm diameter, 100 mm long) shall have adequate clearance from hazardous parts.
D	Protected against access with a wire	The access probe (1.0 mm diameter, 100 mm long) shall have adequate clearance from hazardous parts.

3.1.2 Test probes

The access probes have been newly defined in EN 60529 / IEC 60529 [1.1]. They form part of a system of test probes described fully in EN 61032 / IEC 61032 comprising a total of 18 selected variants from the IEC standards.
The access probes listed in Table 3.1.2 are used in the IP Code.

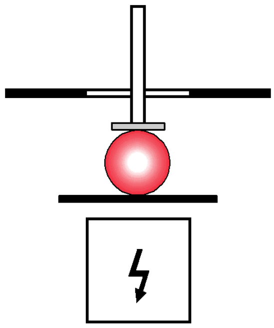
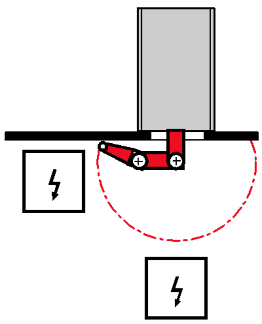
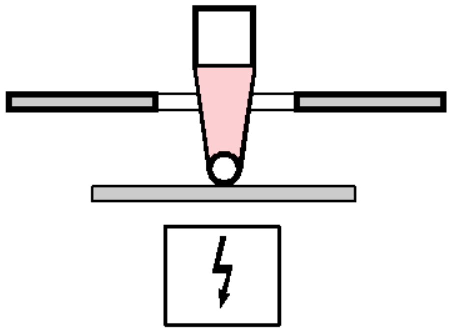
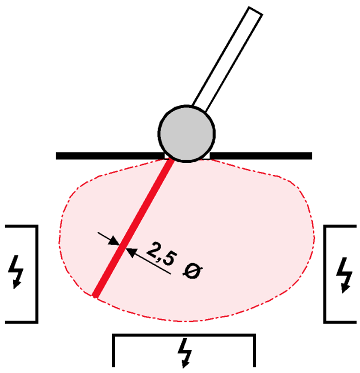
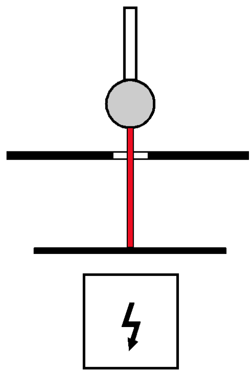
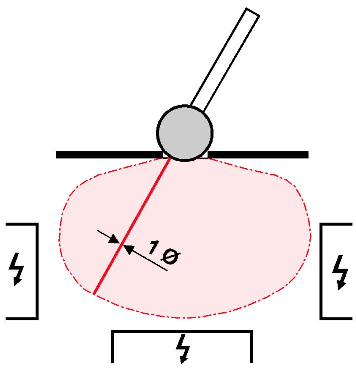
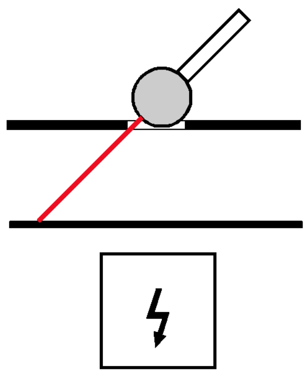
Table 3.1.2 Access probes for testing the protection against access in the IP system

Protection against access with	Access probe	Explanation
Back of the hand		The plate between the sphere and the handle is not a stop but is provided to protect the tester.
Finger		The “jointed test finger” has two joints; for the purposes of the IP test, it is only to be used up to the first stop face measuring 50 mm x 20 mm, 80 mm along its length, as shown in the illustration.
Tool		The “stop face” takes the form of a 35 mm ∅ sphere; it is intended to simulate the knuckle when the tool or wire is held in the hand.
Wire		

3.1.3 Testing for protection against access in accordance with additional letters

While the first code number generally describes protection offered by restricting the opening widths in the enclosure, the additional letters describe ***protection provided by distances or barriers***. Table 3.1.3 explains the test using access probes:

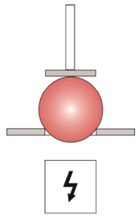
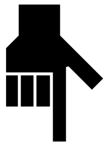
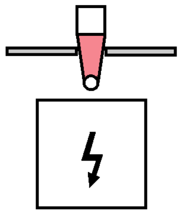
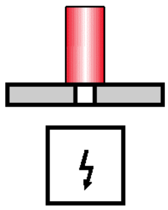
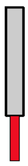
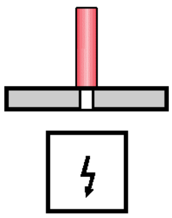
Table 3.1.3 Use of access probes to test the degree of protection against access in accordance with the additional letters in the IP Code

IP code	Protection against access by	
	Distance	Barriere
IPXXA	-	
IPXXB		
IPXXC		
IPXXD		

3.1.4 Testing for protection against access in accordance with the first characteristic numeral

Protection against access is most commonly attained on electrical machinery by the principle of ***limiting the opening widths***. Therefore, the standard specific to electrical machines [1.18] ***intentionally*** *makes no use* of the optional additional letters (Table 3.1.4).

Table 3.1.4 Requirements on the protection against access for the first code numbers IP1X to IP6X

Degree of protection	Protection of persons against access to hazardous parts	
IP1X	Back of the hand 	
IP2X	Finger 	
IP3X	Tool 	
IP4X **IP5X** **IP6X**	Wire 	

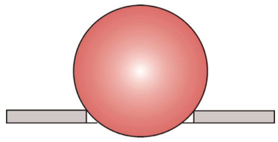
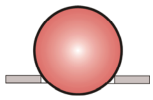
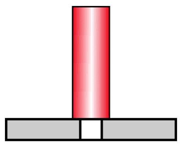
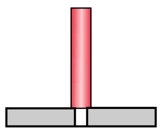
3.2 Protection against ingress of foreign objects

The degree of protection of the machinery within the enclosure against ingress of solid foreign objects is described in the IP Code by the first characteristic numeral.

3.2.1 Large foreign objects

The degree of protection of the machines against penetration by large foreign objects described in Table 3.2.1.

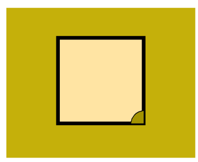
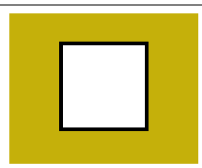
Table 3.2.1
Requirements on the protection against penetration by foreign objects
for the first code numbers IP1X to IP4X

Degree of protection	Protection of the machines against penetration by solid foreign objects	
IP1X	≥ 50 mm ∅	
IP2X	≥ 12,5 mm ∅	
IP3X	≥ 2,5 mm ∅	
IP4X	≥ 1,0 mm ∅	

3.2.2 Dust

The degree of protection of the machinery against dust penetration is described in Table 3.2.2.

Table 3.2.2
Requirements on the protection against dust for the first code numbers IP5X to IP6X

Degree of protection	Protection of the machines against dust penetration	
IP5X	Dust-protected	
IP6X	Dust-tight	

3.2.2.1 Testing for dust protection

The effectiveness of the protection against dust of electrical apparatus is tested and assessed in accordance with [1.1].

The standard "totally enclosed design" of electrical machines corresponds degree of protection IP54. The difference between this degree of protection and special degree of protection IP65 becomes clear from a comparison of the acceptance conditions.

The ***dust chamber*** test (Figs 3.2.2.1.1 and 3.2.2.1.2) involves exhausting air from the inside of the motor under test to create a vacuum of up to 20 mbar such that 80 to 120 times the free air volume is exhausted over two hours. If 80 times the volume of the test piece cannot be exhausted over two hours, the test is extended to a maximum of eight hours.

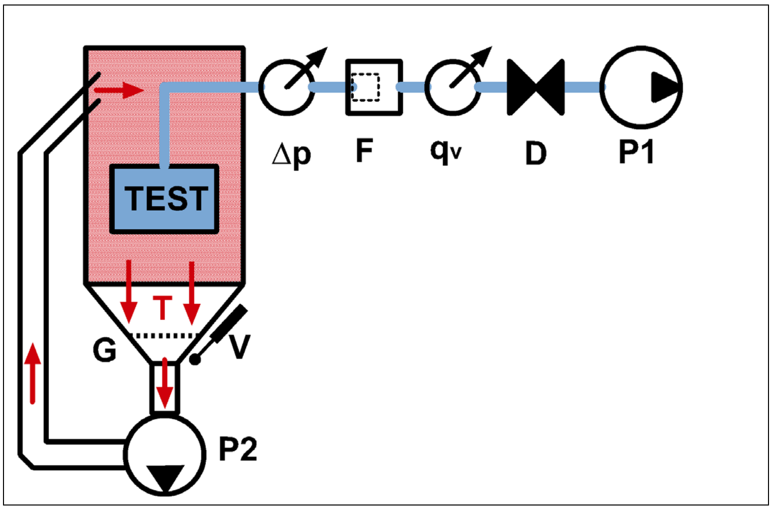


Fig. 3.2.2.1.1
Principle of dust test in accordance with EN 60529 / IEC 60529

TEST	Test specimen
T	Talcum powder max. 75 µm (2 kg/m³ of chamber)
P2	Dust circulation pump
V	Vibrator to dislodge settled dust
G	Guard screen
P1	Vacuum pumpr
Δp	Vacuum gauge (max. 20 mbar)
F	Dust filter
q_v	Air flow meter(max. 60 $V_{test\ piece}$/h)
D	Throttle

IP5X Dust-protected

Penetration of dust is not fully prevented, but dust may not penetrate in such quantities that the correct operation of the motor or safety is impaired.

Acceptance conditions:

The degree of protection is satisfactory if visual inspection indicates that dust has not collected in such quantities or in locations that would impair correct operation of machinery or safety ***given any different type of dust***.

With the exception of certain circumstances clearly defined in the relevant product standard, dust must not settle where it could cause leakage currents.

IP6X Dust-tight

There must be no penetration of dust.

Acceptance conditions:

The degree of protection is satisfactory if, upon conclusion of the test, no visible dust has settled inside the enclosure.

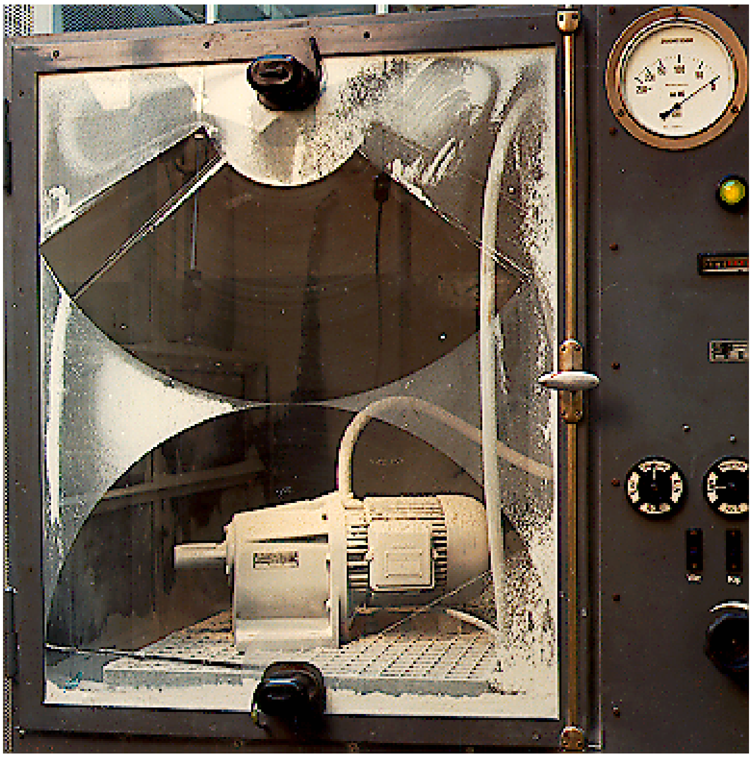


Fig. 3.2.2.1.2
Dust chamber to test dust rotection in accordance with EN 60529 / IEC 60529

3.2.2.2 Gasket on the terminal box
The following should be checked for motors operating in areas at risk from dust:
- ☐ Do the gaskets fitted at the works (Fig. 3.2.2.2.1) offer any dust protection?
- ☐ Are the captive gaskets fitted at the works undamaged at the mating surfaces between the terminal box and stator housing on the one side and the terminal box cover (Fig. 3.2.2.2.2) on the other side?
- ☐ Are the cable entry compression glands fitted at the works adequate for the conditions on site and correctly installed?

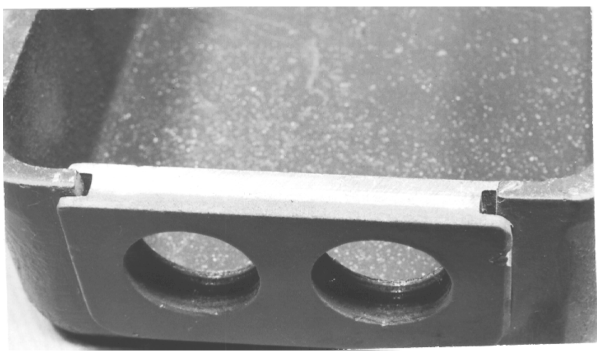


Fig. 3.2.2.2.1
Unsuitable entry elements providing no dust protection

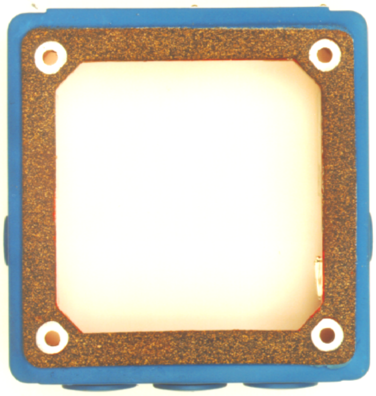


Fig. 3.2.2.2.2
Self-adhesive cork-rubber surface gasket between the mating surfaces of the terminal box
Degree of protection IP6X

3.2.2.3 Sealing the rolling contact bearings

The causes of failure on electrical machines and rolling contact bearings may deviate from the statistics quoted in Figs 3.2.2.3.1 and 3.2.2.3.2 depending on the industrial sector, operating mode and manufacture: the fact remains that rolling contact bearings fail relatively frequently ***due to contamination***.

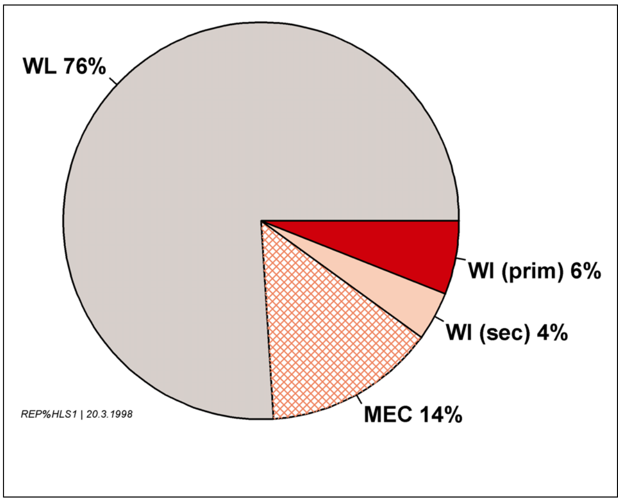


Fig. 3.2.2.3.1
Proportion of causes of damage found on motors under repair by HÜLS AG

WL Rolling contact bearings
MEC Mechanical parts
WI Winding

Source: paper given by *Wagner* at the ABB seminar of experts in the field of explosion hazards, 1990

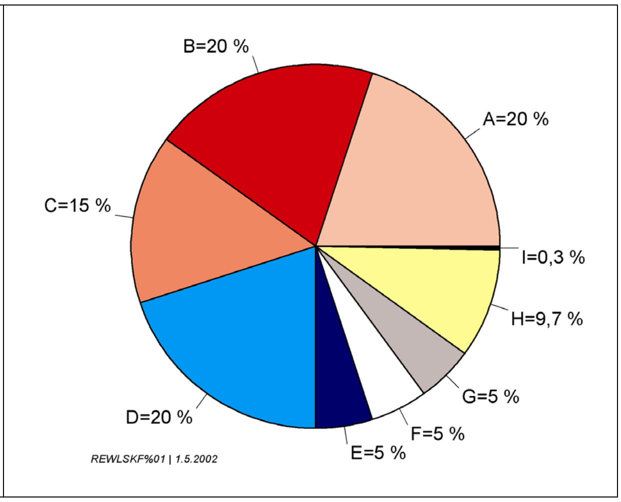
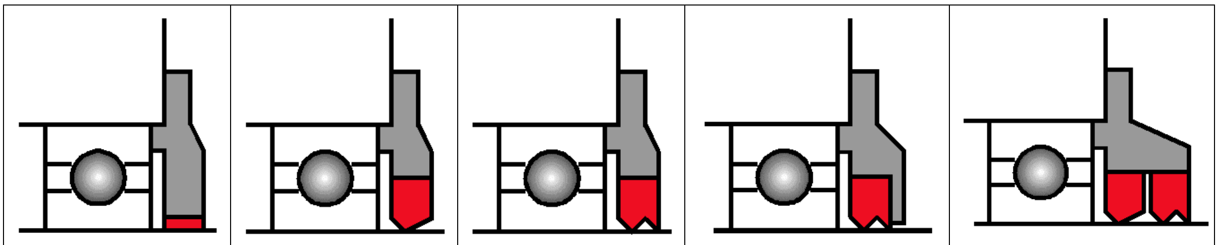


Fig. 3.2.2.3.2
Causes of failure for rolling contact bearings (source: SKF)

A Lubricant unsuitable
B Lubricant aged
C Lubrication poor
D Contamination by solids
E Contamination by liquids
F Faulty assembly
G Consequential damage
H Bearing type unsuitable
I Defective material or production

The seal on rolling contact bearings takes on a particular importance where machines are operated in areas at risk from dust (Fig. 3.2.2.3.3).



Gap seal with limited protection against dust	Rubber (elastomer) shaft seal	Shaft seal with dust lip (gap packed with grease)	Shaft seal with additional mechanical protection	Double shaft seal (gaps packed with grease)

Fig. 3.2.2.3.3 Different levels of sealing rolling contact bearings against dust

3.2.2.4 Restriction of cooling

Dust, particularly fluffy dust, can seriously impair cooling if it settles in air inlet openings, blocks ventilation ducts (**Fig. 3.2.2.4**) or if upstream filters are not cleaned in good time.

Fig. 3.2.2.4
Severe impairment of cooling on a surface-ventilated motor due to partial blockage of the cooling fins

3.2.2.5 Dust explosion protection

In zone 10 and 11 or 20, 21 and 22 areas at risk from dust explosion, the degree of dust protection is particularly tightly controlled by regulations [1.19] and laws [1.20]. Full details on this topic are provided in [2.21].
Minimum degrees of protection are prescribed, according to the zone and conductivity of the dust, as shown in Table 3.2.2.5.

Table 3.2.2.5 Specification for the dust tightness of "tD" dust explosion protected electrical apparatus to present IEC 61241-14 and future EN 50281-1-2

International standards	Zone 20	Zone 21	Zone 22 Dust	
			conductive	non-conductive
IEC 61241-1 Practice A	IP6X	IP6X	IP6X	IP5X
EN 50281-1-2	IP6X	IP6X	IP6X	IP5X

3.3 Protection against ingress of water

The degree of protection of the machinery within the enclosure against the damaging effects of penetration by water is described by the second code number in the IP code. The standard speaks specifically of ***water*** and not ***fluids*** for good reason; particular requirements, such as the protection against corrosive solvents (e.g. cutting liquids or coolants) require a specification in the relevant product standard or an agreement between the manufacturer and the customer (user). Tables 3.3.1 and 3.3.2 provide an overview of testing for water protection.

Table 3.3.1 Requirements on the protection against water for the second code numbers IPX1 to IPX4

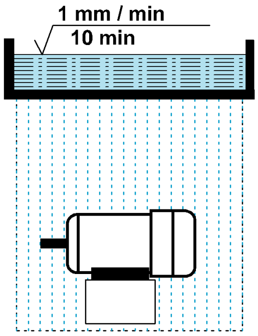
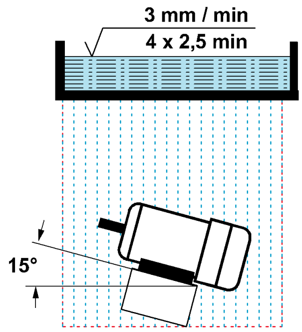
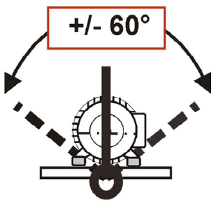
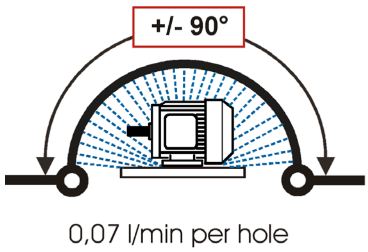
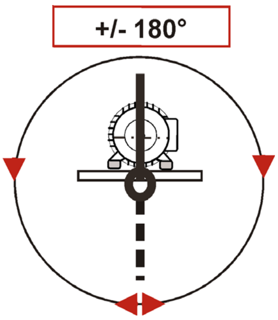
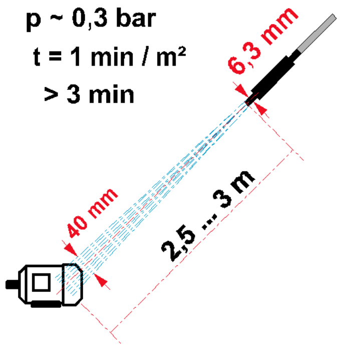
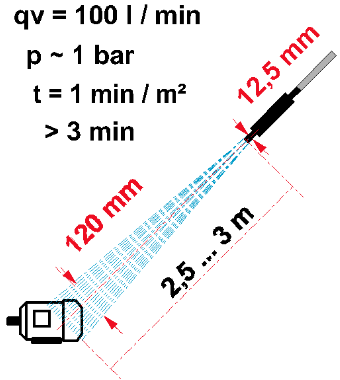
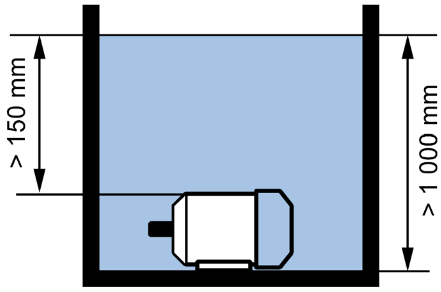
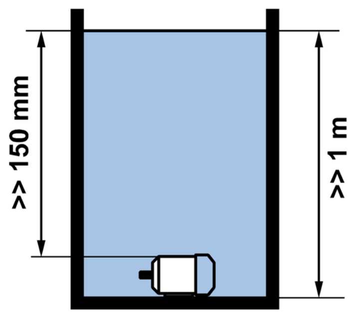
Degree of protection	Protection against	Principle of test
IPX1	dripping water	
IPX2	dripping water at 15° inclination	
IPX3	spraying water	
IPX4	splashing water	 

Table 3.3.2 Requirements on the protection against water for the second code numbers IPX5 to IPX8

Degree of protection	Protection against	Principle of test
IPX5	water jets	**qv = 12,5 l / min** **p ~ 0,3 bar** **t = 1 min / m²** **> 3 min** 
IPX6	powerful water jets	**qv = 100 l / min** **p ~ 1 bar** **t = 1 min / m²** **> 3 min** 
IPX7	temporary immersion in water	*t* = 30 min 
IPX8	continuous immersion in water	***t*** = ∞ IPX8 > IPX7 

3.4 Conversion of the entry thread from Pg thread to metric

Entry elements (***threaded glands***) used to seal the cable as it enters the wiring space are important factors in the IP degree of protection.
The transitional period for the use of ***conduit threads (Pg)*** in accordance with standards expired in Europe at the end of 1999. The special thread is now replaced by a ***metric ISO fine pitch thread***.
Virtually the entire range of electrical apparatus is affected by this changeover: switch cabinets, distributors, household consumer units, junction boxes, appliances, electric motors etc.
This section deals with the effects of this change to the standard and is intended to ease the transition to the new designations.

3.4.1 Graduation of nominal sizes and sealing range

Conduit threads roughly cover a ***sealing range*** (outer cable diameter) of 5 to 46 mm in *10 sizes*; the metric variants cover practically the same range of 4 to 42 mm in only ***8 nominal sizes***. Fig. 3.4.1 shows the sealing range of the new metric threaded unions.

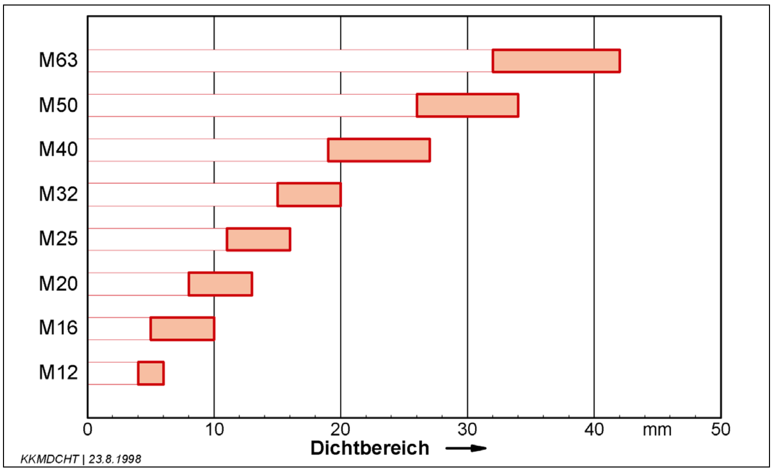


Fig. 3.4.1
Sealing range of the 8 nominal sizes of metric threaded unions

3.4.2 Interchangeability of the maximum cable diameter

Where the largest cable diameter that can be inserted is decisive in the selection of the entry element, the assignment given in Tables 3.4.2.1 and Fig. 3.4.2.2 is decisive.

Table 3.4.2.1 Substitution of Pg threads as a function of the cable diameter

Pg	7	9	11	13,5	16	21	29	36	42	48
M	12	12(16)	16	20	25	32	40	50	63	63

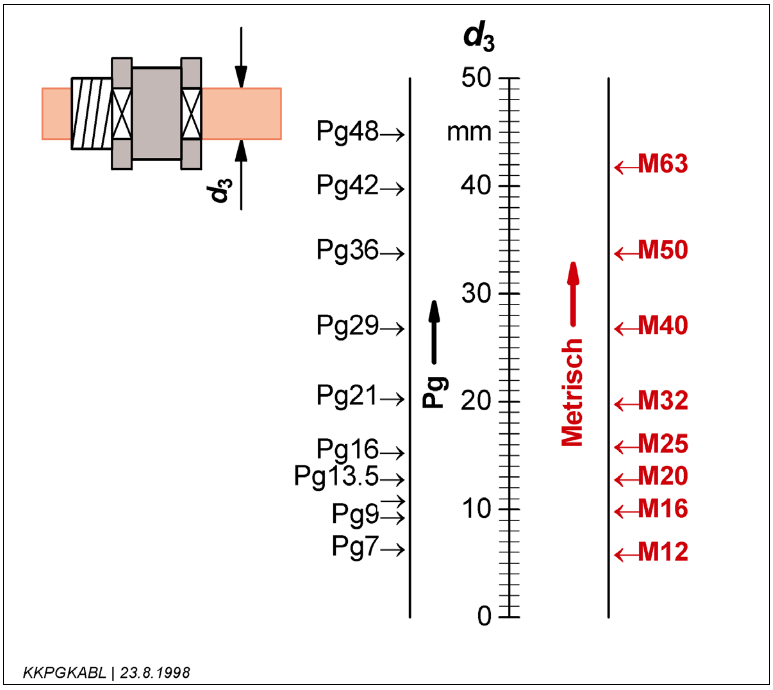


Fig. 3.4.2.2
Comparison of the largest cable diameter d_3 that can be inserted in accordance with the standard

3.4.3 Entry into the terminal boxes of standard motors

The dimensional standards for the entry thread of standard motors (Table 3.4.3) were changed with the introduction of DIN 42925, “Cables entering the terminal boxes for three-phase motors with rated voltages from 400 V to 690 V”:

Table 3.4.3 Assignment of entry threads to the terminal boxes of surface-cooled standard motors with shaft heights of 90 to 315 mm

Shaft height mm	Thread in accordance with DIN 46319 (metric)	Thread in accordance with DIN 46320 (Pg)	Number of entries
90	M25	Pg16	1
100	M32	Pg21	2
112	M32	Pg21	2
132	M32	Pg21	2
160	M40	Pg39	2
180	M40	Pg29	2
200	M50	Pg36	2
225	M50	Pg36	2
250	M63	Pg42	2
280	M63	Pg42	2
315	M63	Pg48	2

4 Ambient conditions

The ***environmental influences*** acting on electrical machines may vary greatly at the installation location. This must be taken into account by appropriate planning, selection and installation. The selection of the correct IP degree of protection (see clause 3) plays an important role but is not the sole consideration.
Since the insulation of the winding (thermal classification) is an important prerequisite in a motor's service life, we shall discuss this point first.

4.1 Thermal classification

The various materials used in the insulation of electric motors are divided into ***thermal classes*** (formerly ***insulation classes***) in accordance with Appendix A of the revised DIN VDE 0530 Part 1 dated July 1991 and IEC 60085 (Table 4.1.1).
The ***limits of temperature rise*** are allocated on the criterion that, under continuous loading, a long life is ensured with an adequate factor of safety. Thus, a continuous working temperature of 130 °C is permissible for motors with the standard Class B insulation. Assuming a maximum permissible ***ambient temperature*** of 40 °C, the maximum temperature rise of the winding must not exceed 80 K when measured by the resistance method. The 10 K safety margin is to allow for possible unevenness in temperature distribution (***hottest spot***) (Fig. 4.1.2).

Table 4.1.1 Thermal classification of insulating materials

Thermal classification (insulation class)	Insulating material temperature limit °C	Winding temperature rise limit K
B	130	80
F	155	105
H	180	125

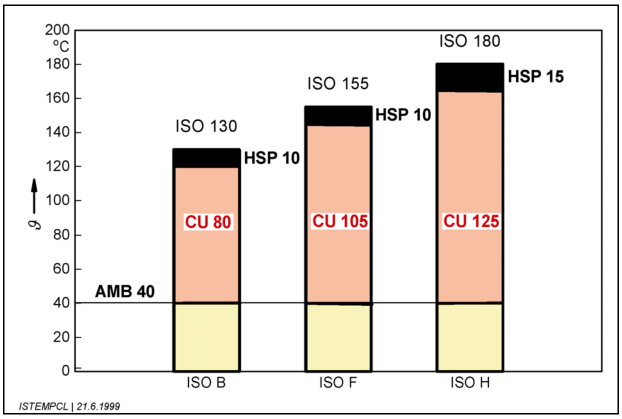


Fig 4.1.2
Insulating material temperature limit (ISO) and winding temperature rise limit (above ambient temperature AMB 40 °C) for A.C. windings (CU) on motors up to 200 kW,
measured by the resistance method in accordance with EN 60034-1 / IEC 60034-1 and IEC 60085 with allowance for “hottest spot” (HSP)

Fig. 4.2.1 shows that the theoretical ***service life of an insulating material*** drops to approximately 50 % if the temperature is raised by 10 K.
If a higher temperature class (e.g. F or H) is chosen, two possible benefits can be obtained:
- ☐ a higher loading capacity with the same theoretical service life,
- ☐ a longer service life and better reliability for the same loading.

The improved insulation is usually adopted to obtain higher reliability of service under abnormal operating conditions.

4.2 Ambient temperature

4.2.1 Initial position in accordance with the standards

According to the standards for electrical machines [1.6, clause 11], ambient temperatures between –15 and +40 °C are regarded as “normal”.

As far as the value for the upper limit of 40 °C is concerned, one should bear in mind that the previous national REM (regulations for electrical machinery) held an upper limit of 35 °C to be appropriate and that even this value was qualified by the phrase “on isolated hot summer days”.

Insulating materials have undergone considerable improvements over the past thirty years. However, the *Montsinger* law which states that the service life of an insulating component halves for every 8 to 10 K rise in temperature still applies.

The thermal rating of a new insulating material is based on standardized series of tests resulting in the types of ***service life graphs*** shown in Fig. 4.2.1. A theoretical service life of 20,000 hours is used as the benchmark for classification into temperature classes. This figure is ***purely for comparison***; experience shows that the actual service life of an electrical machine's insulation system is far longer.

Comparable laws also apply to the “service lives” of lubricants where “failure” is not at all easy to define (see Fig. 9.10).

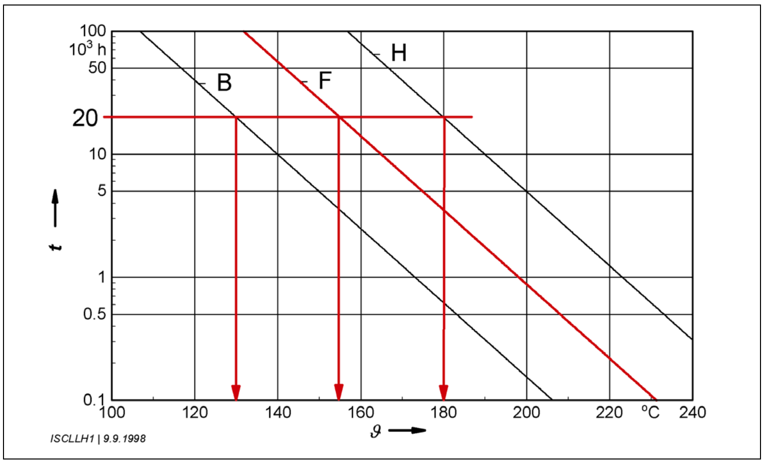


Fig 4.2.1
Theoretical service life *t* of thermal class B, F and H insulating components at different temperatures ϑ

4.2.2 Measures at high ambient temperatures

Strictly speaking, the standard only requires special consideration to be given to the design of electric drives where ambient temperatures are above 40 °C. Attention to the following points is recommended to increase the reliability of drives ***required to operate continuously at the limit of their rated output*** in warm surroundings:

Choice of a higher thermal class for the winding

The motor may reach its full rated temperature rise and can, therefore, operate at full rated output. It has been the intention not to exploit the full range set by the standard in the recommendations given in Fig. 4.2.2.1 (see section 4.2.1).

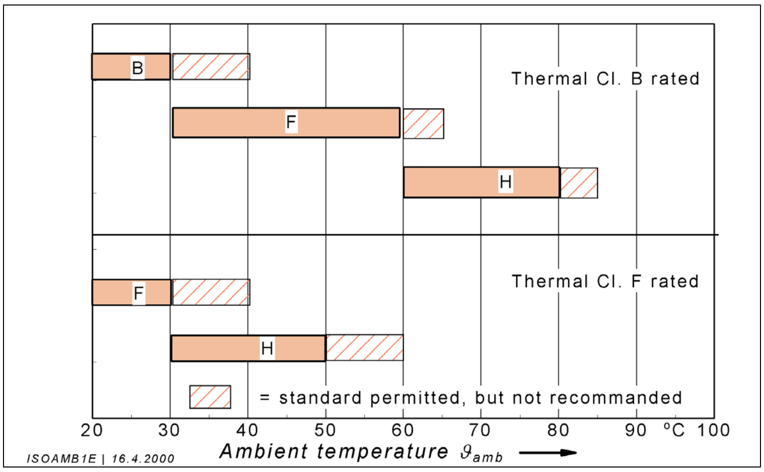
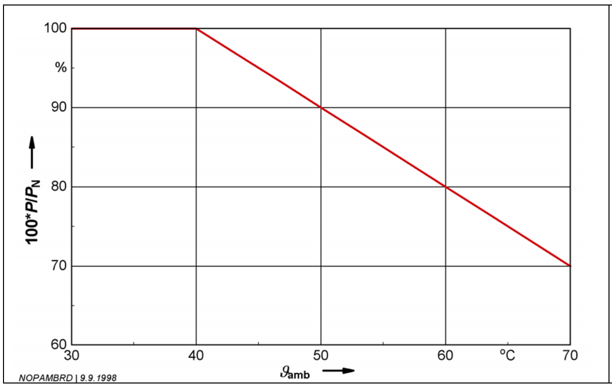


Fig. 4.2.2.1
Recommendation for the choice of temperature class for increased ambient temperature and maintenance of rated output
Cl. B Thermal classification B
Cl. F Thermal classification F

Reduction in the rated output

A lesser increase in the winding temperature occurs when the rated output is reduced; the limit temperature for the normal thermal classification is not exceeded (Fig. 4.2.2.2).



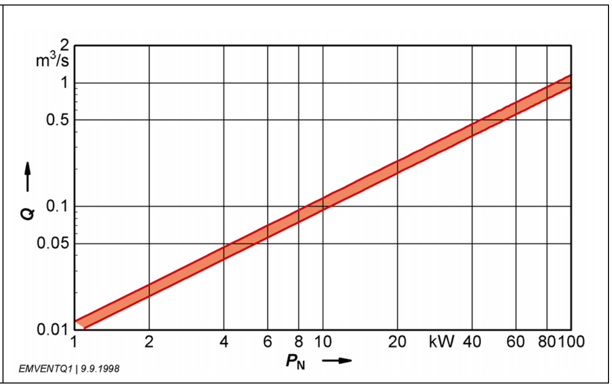


Fig. 4.2.2.2
Reduction in the rated output P_N at abnormally high ambient temperatures ϑ_{amb}

Bild 4.2.2.3
Guide values for the cooling air supply Q required to cool 4-pole standard motors for a rise in the cooling air temperature of approximately 20 K

Cold fresh air feed

Depending on the local conditions, it may be advantageous to arrange for a supply of cooling air for very high room temperatures. The literature agrees on the following ***cooling air requirement*** specified for a moderate rise in the cooling air temperature of approximately 20 K:

Q_1 = 0.04 to 0.05 m³/s per kilowatt loss of power.

The cooling air supply Q required for normal levels of efficiency of a standard 4-pole motor is calculated in accordance with Fig. 4.2.2.3.

Rolling contact bearing lubrication

Improving the thermal class of the insulating material is not enough in view of the accelerated deterioration of standard lubricants at high temperatures.The time interval for re-lubrication must be shortened or special lubricants employed.

4.2.3 Measures at low ambient temperatures

At low ambient temperatures (generally below –15 °C), lubricants used for bearings and gears tend to solidify so that running-up when the motor is started after long periods of rest is impeded.
Should more power be required at low temperatures, this should be taken into account when determining the rating of the drive. In drives where breakaway torques have been reduced to achieve a gentle run-up on starting, it may become necessary to ***heat the gearbox*** or fill with a special ***low-temperature lubricant***, even at temperatures around freezing point. This applies in particular to low-power geared motors.
The following points may be useful in this respect:

- ☐ If low temperature conditions occur only during transport, storage or during non-operational periods and the motor temperature is raised slowly to a value above – 15 °C before it is started, a standard drive with normal lubrication may be used.
- ☐ Special measures are to be taken if reliable starting is to be ensured even when the motor is still at a low temperature:
  - The motor must be considerably over-rated so that is may have sufficient torque to break away, thus freeing the frozen driven machinery or, for example conveyor belt rollers, and, in the latter case, also freeing the belt from the guide rollers.
  - Where practicable, the drive should be allowed to run on no-load during non-working periods so that lubricated elements do not reach too low temperatures and cause other parts to freeze together.
  - Once the mains supply has been switched off, the stationary motor winding may be heated to prevent the lubricants from cooling and solidifying. For this, the winding may be connected to a stepless or tapped variable A.C. voltage of approximately 20 % of the rated voltage (Fig. 4.2.3.1).
  - This heating voltage U_H should be chosen such that the heating current I_H is at a maximum of 65 % of the rated current shown on the rating plate. In cases of doubt, please quote the motor type and serial number and the manufacturer will gladly advise.
  - The motor should be checked during the first 3 to 5 hours of heating to ensure that there is no overheating due to the choice of an unduly high heating voltage.

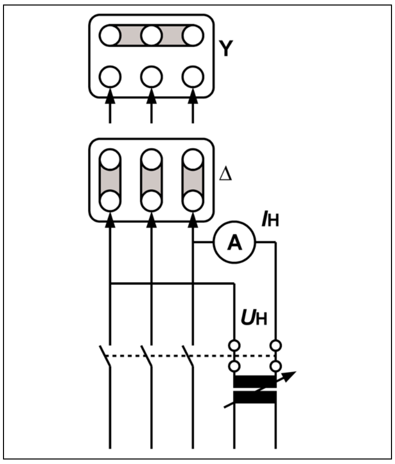


Fig. 4.2.3.1
Circuit diagram for standstill stator heating;
Guide values for
Heating voltage U_H (guide value 20 % of U_N)
Heating current I_H (guide value 65 % of I_N)

Lithium soap base rolling contact bearing greases with a broad temperature application range are commonly used in electrical motors. The use of special greases may be necessary in special cases of extreme low or high temperatures as shown in Fig. 8.5 – please seek the advice of a lubricants expert.
The temperature limits of the *plastics* commonly used these days for the fans on small and medium machines must also be observed. The material can become brittle at low temperatures and soft at very high temperatures.
Fig. 4.2.3.2 provides guide values for the application ranges of common materials used for the fan blades of electrical machines.

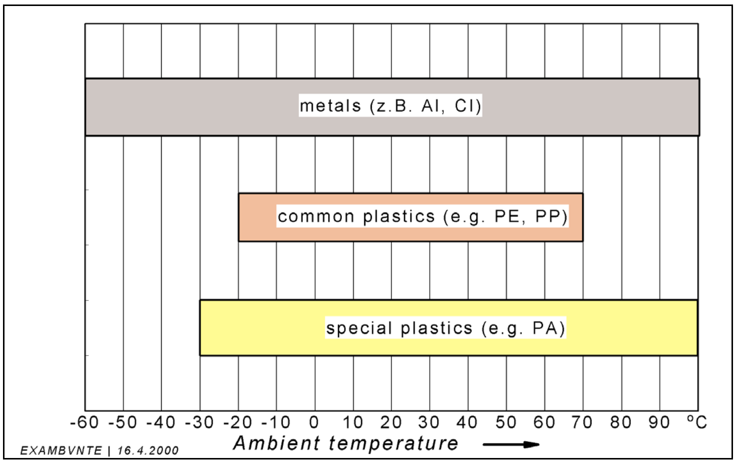


Fig. 4.2.3.2
Guide values for the temperature application range of fan materials

ALU	Aluminium
GG	Grey cast iron
PE	Polyethylene (e.g. Hostalen)
PA	Polyamide (e.g. Ultramid)
PP	Polypropylene (e.g. Hostalen)

4.3 Site altitude

The rating data of electric motors applies for site altitudes up to 1000 m above sea level. The reduction in heat dissipated by the cooling air must be taken into account at higher altitudes.The following rules do not, therefore, apply to non-ventilated special designs (cooling method IC410). The limit temperature of windings must be reduced at site altitudes above 1000 m as given in Fig. 4.3.1.

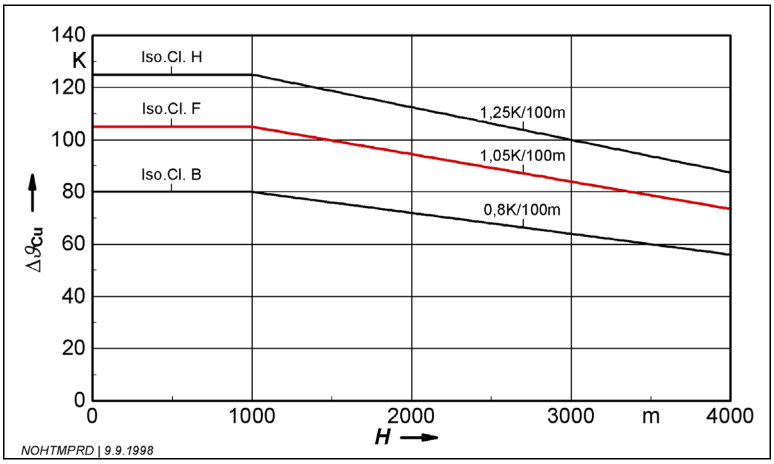


Fig. 4.3.1
Temperature rise limit $\Delta\vartheta_{Cu}$ of temperature class B, F and H windings at a site altitude *H* of up to 4000 m and an ambient temperature of 40 °C in accordance with EN 60034-1 / IEC 60034-1, subclause 16.4.1

If one accepts the results obtained from experience and assumes that a reduction of the temperature rise by 1 K requires a power reduction of 1 %, Table 4.3.2 gives the guide power values for thermal classes (insulating material classes) B and F.

Table 4.3.2
Guide values for the relative utilization P/P_N of class B and F ventilated electric motors at site altitude H between 1000 and 4000 m above sea level and at an ambient temperature of 40 °C

H	P/P_N	
m	B	F
1000	1	1
1500	0,96	0,95
2000	0,92	0,90
2500	0,88	0,85
3000	0,84	0,80
3500	0,80	0,75
4000	0,76	0,70

However, it can usually be assumed that the maximum permissible ambient temperature of 40 °C will ***not occur continuously*** at high altitude. If the limit values shown in Fig. 4.3.3 and Table 4.3.4 are not exceeded, the drive may be loaded to its full rated output P_N. This permits the adoption of a simplified procedure for all those concerned – manufacturers, installers and users.
EN 60034-1 / IEC 60034-1, subclause 16.3.5, includes the following information: If the machine is to be operated at a site altitude of between 1000 m and 4000 m and the maximum temperature of the coolant is not specified, the following should be assumed: the reduction of the cooling effect due to the altitude will be compensated by the reduction of the maximum ambient temperature below 40 °C. The specified site altitude and the assumed maximum ambient temperature must be indicated on the rating plate.

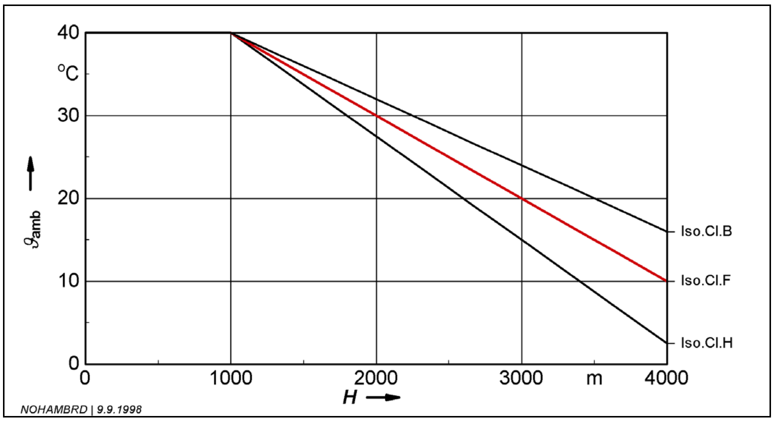


Fig. 4.3.3
Maximum permissible coolant or ambient temperature ϑ_{amb} for utilization of the full motor rating $P = P_N$ at site altitudes H from 1000 to 4000 m above sea level; in accordance with EN 60034-1 / IEC 60034-1, subclause 16.3.5

Table 4.3.4
Maximum permissible coolant or ambient temperature ϑ_{amb} for utilization of the full motor rating $P = P_N$ at site altitudes H from 1000 to 4000 m for temperature classes B, F and H

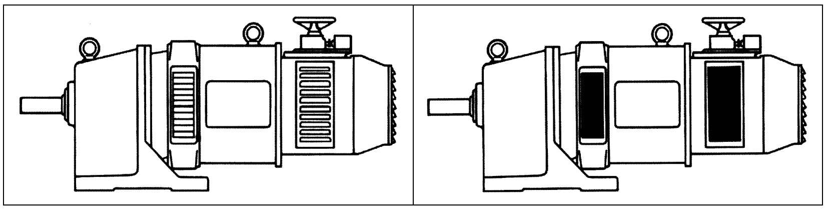
H	ϑ_{amb} in °C		
m	B	F	H
1000	40	40	40
1500	36	35	34
2000	32	30	28
2500	28	24	21
3000	24	19	15
3500	20	14	9
4000	16	9	3

4.4 Splashing water, flooding

Electrical machines are very often subjected to water in everyday operation, whether from splashing water during processing and cleaning, occasional inadvertent flooding or even continuous underwater operation.
What situations are covered by the standardized degree of IP protection – should special measures be agreed with the manufacturer? This section aims to provide a few answers to these questions. The specifications for the degree of IP protection against penetration by water are based on subclause 3.3. Reference is also made to [2.1].

4.4.1 Ship deck installation – supplementary letters S and M

The ***supplementary letters*** S and M were included in the standard specifically for electrical machines. The following explanation quotes from IEC 60034-5:
"In special applications (such as machines with open-circuit air cooling for ship deck installation with air inlet and outlet openings closed during standstill) code numbers may be followed by a letter indicating whether the protection against harmful effects due to penetration by water was verified or tested for the machine not running (letter S) or the machine running (letter M).In this case the degree of protection in either state of the machine shall be indicated, for example IP55S/IP20M. The absence of the letters S and M shall imply that the intended degree of protection will be provided under all normal conditions of use."



IP20M for operation in port

IP55S for standstill when sailing in high seas

Fig. 4.4.1
Example for the application of the suffix letters S and M: open-circuit air-cooled winch motor for ship deck installation

4.4.2 Weather-protected machines – supplementary letter W

The letter W is used for open-circuit air-cooled machines operated under specified weather conditions and with additional protective measures or equipment.
For more detailed explanations, see [1.1], [2.1].

4.4.3 Icing

The formation of ice, for example following penetration by snow or water where the machine has been installed outdoors, can severely impair the function of electrical equipment. A thin layer of ice can impair the movement of elements, especially those which operate internal components from the outside (such as tappets, thrustors, shafts and axles). In this instance, a gap which has been kept intentionally large is often poses less risk than a gap which has been kept very small for the purposes of sealing (Fig. 4.4.3). The formation of ice on externally ventilated motors can lead to blocking. This second possibility also serves to demonstrate that a high degree of IP protection alone cannot solve the problem, nor is standstill heating successful in every case. For this reason, icing is explicitly excluded from the field of application of the IP standard.

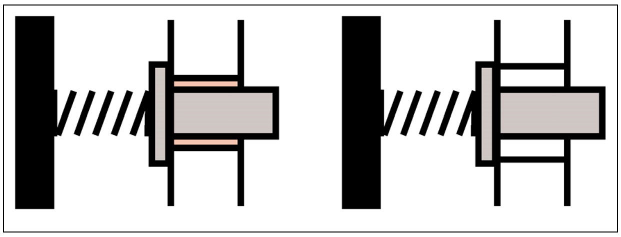


Fig. 4.4.3
Button at risk of icing

Left: small gap = high
Right: large gap = low

Notes for the user:
A high degree of protection in itself offers no protection against icing. Narrow gaps on external operating elements are particularly at risk. Watertight devices with appropriate seals (such as diaphragms) are to be preferred. Agreement with the manufacturer is highly recommended.

4.4.4 Water jets

If a unit is occasionally cleaned using a water jet running off the normal mains pressure, a motor with splashing water or water jet protection to IPX4 or IPX5 will suffice.
If, on the other hand, a product is ***continuously*** subjected to a water jet in the course of the manufacturing process, special degree of protection IPX6 (Fig. 4.4.4) is recommended for the drives in the area affected by the water jet.

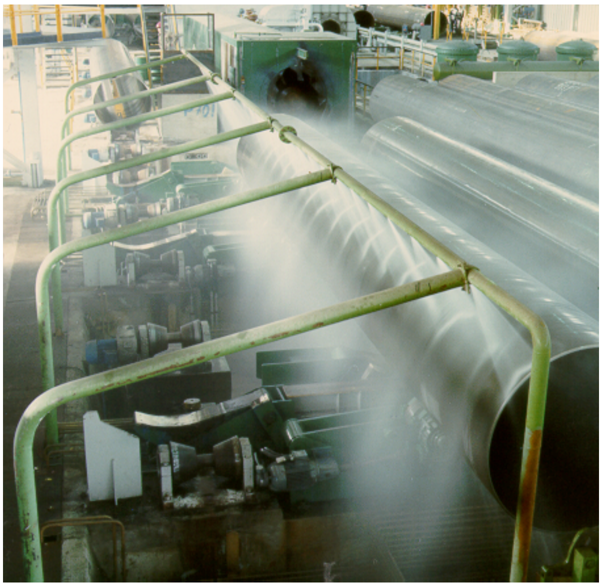


Fig. 4.4.4
Descaling large pipes using a high-pressure water jet
Roller table motors and auxiliary drives to degree of protection IP66

4.4.5 High-pressure cleaning and detergents

For applications involving the manufacture and preparation of foodstuffs (e.g. fish on deep-sea trawlers), high-pressure water jets (e.g. up to 10 bar) are occasionally used. Water damage is to be expected where conventional electrical machines are subjected to a water jet of this type.
If ***chemical cleaning agents*** have been added to the water (e.g. in car washes, Fig. 4.4.5), the water is given a particularly “fine head” and can penetrate dirt and grease – even standard sealing compounds on the terminal box or the bearing flange.
EN 60529 / IEC 60529 therefore specifies the following: "The tests for the second code number shall be carried out using fresh water. The actual protection offered may not be sufficient if cleaning processes employ high pressure and/or solvents.

Fig. 4.4.5
Special protective measures are recommended for electrical equipment located in the area directly affected by the water from a car wash.

Picture reference:
California Kleindienst Autowaschtechnik

4.4.6 Continuous drenching

Cooling towers serve to cool industrial water heated by a production process and which is returned to the circuit for economic or ecological reasons. Fig. 4.4.6.1 shows the principle mode of operation. It is inevitable that a small portion of the water held in the cooling air escapes upwards. This can be seen as a distinctive “cloud” over the cooling tower under certain weather conditions. This water wets the fan drive and places a constant stress on the seals.
Continuous running duty under these conditions places cooling tower drives in one of the most arduous drive scenarios and provides a classic example of the application of degree of protection IP66 (Fig. 4.4.6.2).

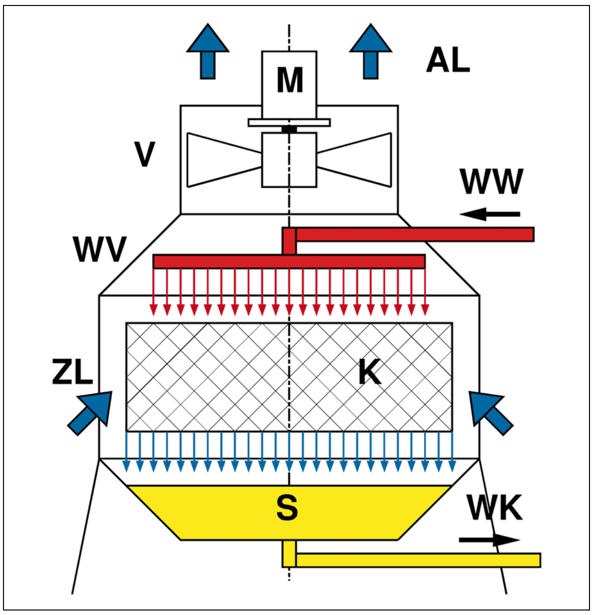


Fig. 4.4.6.1
Concept of operation of a cooling tower

M Motor
V Fan
K Cooling parts
ZL Inlet air
AL Exhaust air
WW Water (warm)
WK Water (cool)
WV Water distributor
S Collecting tank

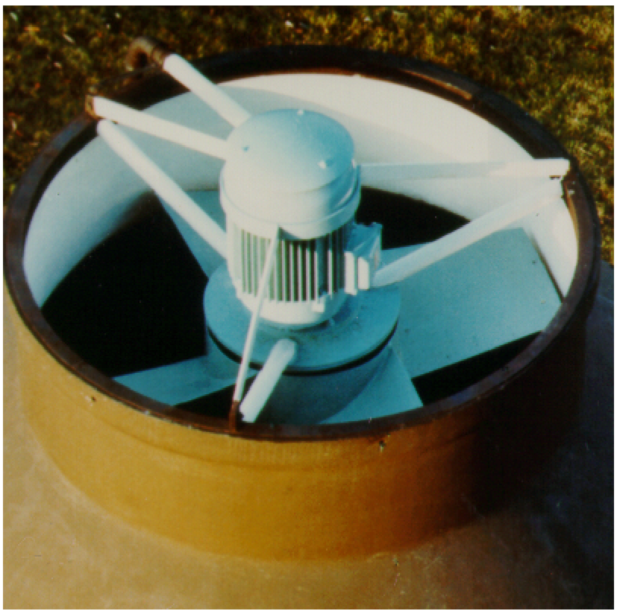


Fig. 4.4.6.2
View of a cooling tower with a single-stage geared motor as the fan drive
Motor with protective roof in V1 arrangement

4.4.7 Intermittent flooding

Sewage treatment works are often sited on river plains and are consequently at risk of flooding. Motors constructed to special degree of protection IP66 do not, in fact, offer any guarantee of being able to withstand intermittent flooding but experience shows that they do offer a high degree of probability of withstanding intermittent flooding (Fig. 4.4.7).

Fig. 4.4.7
High water in a sewage treatment works with short-term flooding of the drive motors for the scraper gantries and screw conveyors

4.4.8 Minimum degrees of protection in accordance with the installation regulations

The protection of electrical equipment against water is not only important for the function of the equipment but is also of relevance to safety. The installation regulations therefore prescribe minimum degrees of protection for certain applications, quoted here in part.

IPX5 Protection against water jets
Workshop pits cleaned with water jets
Shower rooms (areas 1, 2 and 3)
Car washes
Meat processing plants (where machine parts are hosed directly)
Cheese ripening rooms
Sewage treatment works

IPX6 Protection against powerful water jets
open decks on ships

IPX7 Protection against temporary immersion
Dairies
Saunas (in the spraying area)
Slaughterhouses
Swimming pools (where subjected to hosing)
Washrooms

A full list of the requirements according to the operating area may be found in the book [2.19] and provides a useful and comprehensive reference work for day-to-day practice.

4.5 Condensation

Condensation is often cited as the cause of damage to the winding resulting from water or humidity. It is worth analysing the processes critically to gain an objective insight into the causes.

4.5.1 Physical process

The processes which cause the formation of condensation are best explained using the simplified ***Humidity status graph*** in accordance with IEC 60721-2-1 (Fig. 4.5.1).

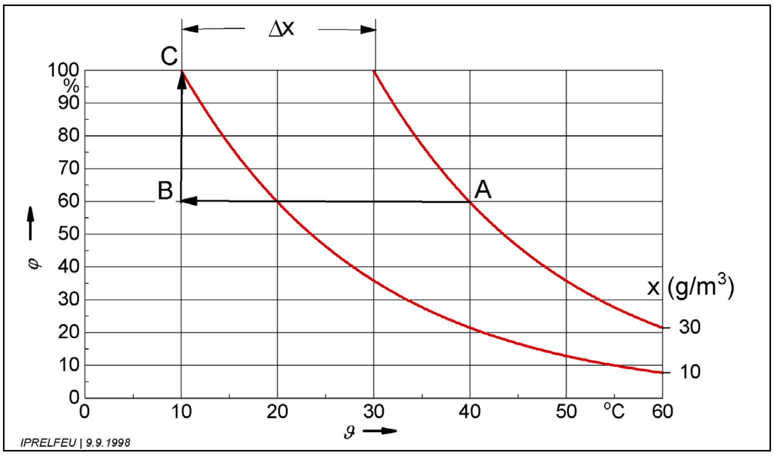


Fig. 4.5.1
Simplified humidity status graph in accordance with IEC 60721-2-1
x Absolute humidity (water vapour content)
φ Relative humidity
ϑ Temperature

The curves on the graph (reduced to two for clarity) show the stable condition of humid air. An ***absolute humidity x*** of 30 g/m³, for example, may be present vapour in air at 60 °C. The air holds little water in this state; the ***relative humidity φ*** (as a proportion of maximum saturation) is approximately 20 %.

The 100 % *saturation point* is only reached at a temperature of 30 °C – the total volume of water can no longer be held in the air at lower temperatures so a portion of the vapour condenses out as ***condensation*** (dew).

Let air with an absolute humidity of x = 30 g/m³ and a temperature of 40 °C be present in a closed enclosure which is not air-tight (point A in the diagram). The relative humidity is φ = 60 %. If the container and its contents are suddenly cooled to 10 °C (point B), the air will only be able to hold a humidity of 10 g/m³ because it is itself at full saturation at point C (φ = 100 %). The saturation deficit Δx = 30 g/m³ – 10 g/m³ = 20 g/m³ is released in the form of condensation and precipitates mainly on the cold surfaces of the enclosure (inner walls).

4.5.2 Condensation quantity

Absolute humidity fluctuates in nature. In other words, the weight of water (g) per volume of air (m^3) varies between approximately 5 g/m^3 (in Northern Europe) and 30 g/m^3 (at the equator). These figures indicate that the amount of condensation is never very high, even in extreme cases. Fig. 4.5.2 provides guide values for the free volume of air *V* in motors with a shaft height range of 71 to 200 mm and the maximum water vapour content in air, i.e. 600 mg (0.6 g) for an overall size of 200. Only a fraction of this water can form condensation.

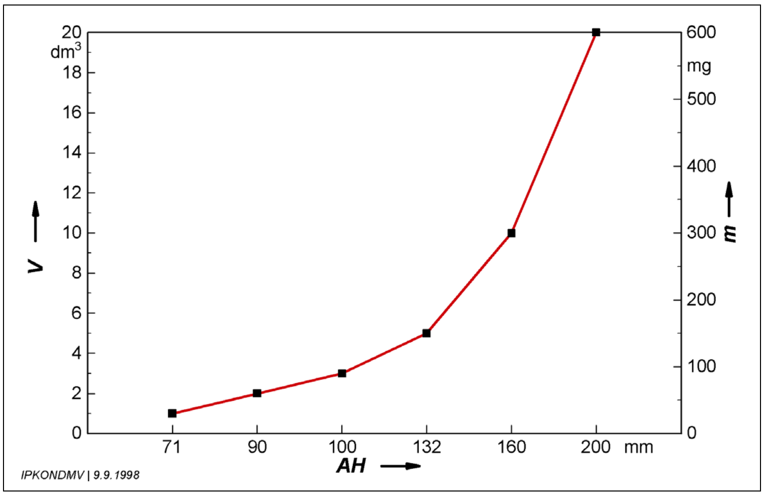


Fig. 4.5.2
Guide values for the free volume of air *V* and the maximum water content *m* in motors with shaft heights *AH* = 71 to 200 mm

Even under repeated heating and cooling, it is physically impossible for condensation to form in such quantities that the winding components are “placed under water”.
As a consequence, this also means that condensate drain holes are superfluous.

4.5.3 Size and position of condensate drain holes

Motor manufacturers have given great consideration to the correct location of condensate drain holes in the past (Fig. 4.5.3). The relevant instructions in their operating instructions spoke volumes:

- ☐ The condensate drain hole should be small enough to prevent penetration by dust and external water: maximum 8 mm in accordance with DIN 40050 as previously applicable; Sample Sheet 1 dated 1963.
- ☐ It must be large enough to prevent blockage caused by rust and dirt: at least 4 to 6 mm.
- ☐ It should be located at the lowest point: no simple requirement for different installation and, above all, for vertical configurations. The notion that water will seep from the upper winding chamber through the slots and the air gap to the lower end winding from where it will drain without causing damage is just as incomprehensible as the effect of a hole in the top end of the laminated core.
- ☐ Seal plugs were introduced because open condensate drain holes clearly cause more damage than they prevent. These ranged from grub screws (which rusted solid), plastic bungs (which are so inaccessible that they can never be opened) through to valves which are supposed to operate yet another electrical lockout device for the motor.
- ☐ Flameproof configurations were required for “flameproof enclosure” type explosion protection.

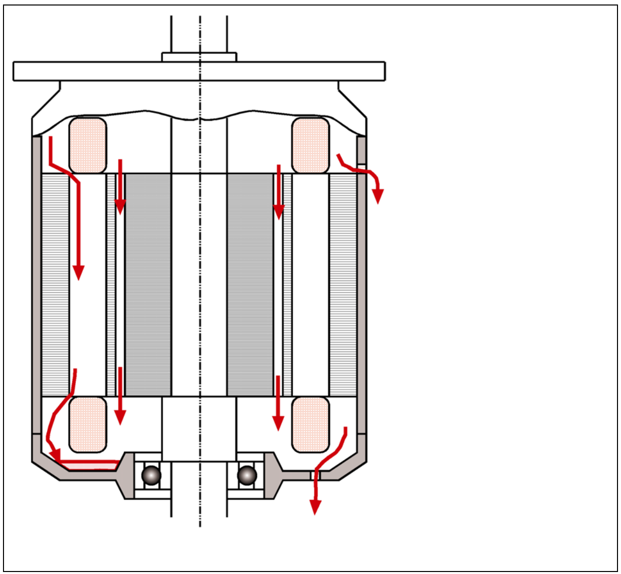


Fig. 4.5.3
Schematic diagram of a machine in V3 configuration with theoretical paths (through the drain holes provided) and actual paths (through the slots and air gap) of the condensation

4.5.4 Protection against condensation

The problems debated so hotly in the past were discussed in such detail in the previous section to throw greater light on the position held today.

- Condensation can ***never be eliminated entirely***.
- Initially the condensation forms a film of moisture on all parts – including the winding – and only in extreme cases does it collect in such quantities that it can be drained off.
- Moisture-resistant, ***non-hygroscopic insulating materials*** and paints are more important that drain holes.
- ***Adequate distances*** must be provided, especially in areas where water may collect (Fig. 4.5.4.1).
- ***Stator standstill heating is advisable*** in extreme cases to prevent sudden and excessive temperature differences. Special heater coils are fitted to medium and small motors for this purpose. The stator winding on smaller machines is usually supplied with single-phase current at approximately 20 % of the rated voltage (see Fig. 4.6).
- An ***air-conditioning connection*** is commercially available for special cases (Fig. 4.5.4.2).
  It acts as a ***breathing aid*** to reduce vacuum pressures, suction water, and the collection of condensation.
  It offers a high degree of IP protection against dust, infiltration water and access as a *drain hole* for penetrating water.

Bild 4.5.4.1
Crowding between the end winding and bearing bracket give rise to flashovers in the presence of condensation.
A drain hole would not help in these circumstances.

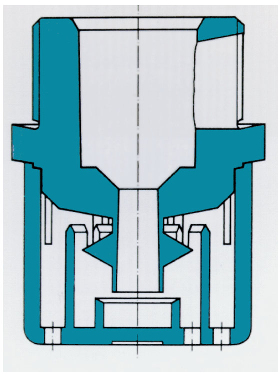


Bild 4.5.4.2
Air-conditioning connection with Pg 16/Pg 21 and M 25/ M 32 threads

Manufactured by STAHL Schaltgeräte GmbH

Decades of experience show that condensate drain holes can safely be omitted provided that these basic principles are followed. Today, condensate drain holes are sometimes only supplied as an option whereas a questionnaire conducted in 1963 showed that more than 80 % of all closed three-phase motors produced in Germany were fitted with condensate drain holes.

4.5.5 Discrimination between condensation, external water and desegregated water

One should not rush to blame condensation for winding damage caused by water or humidity.
The overriding majority of such instances of damage can be put down to infiltration water. If ***rust*** starts to form on fittings, bearing flanges, threads projecting inwards or on contact surfaces of the terminal box, this is a clear indication of infiltration water – particulars when combined with appropriate operating conditions (such as outdoor installation).
It is a less known fact that new windings can generate water ***the first time the motor is started*** if hygroscopic insulating materials has been used (for the lamination insulation, for instance). Research carried out by *Mecklinger* resulted in astonishing quantities of condensation which decreased considerably upon each subsequent warm-up sequence and were not repeated even after prolonged exposure to humidity (Fig. 4.5.5).

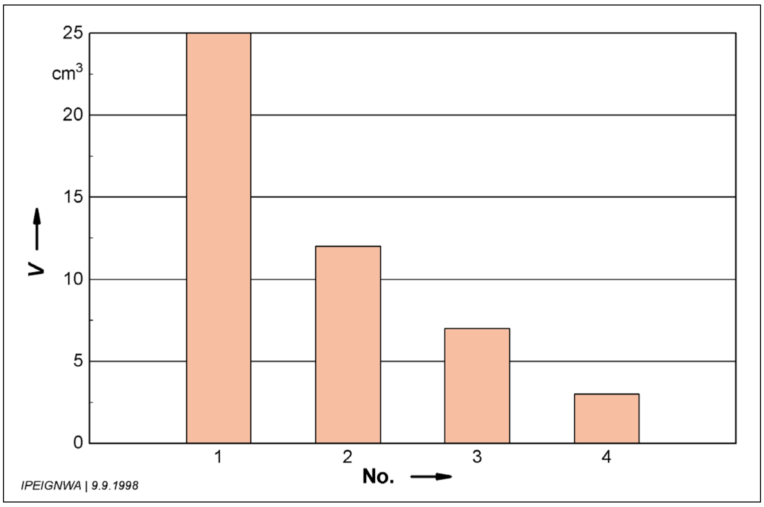


Fig. 4.5.5
Quantity of fluid *V* generated in a three-phase motor with a shaft height of 132 for the first four warm-up sequences after manufacture

4.6 Humidity, tropics, termites

4.6.1 Humidity

Ambient air always holds a certain amount of water in the form of vapour. ***Absolute humidity*** fluctuates in nature. In other words, the weight of water (g) per volume of air (m^3) varies between approximately 5 g/m^3 (in Northern Europe) and 30 g/m^3 (at the equator). The warmer the air, the more moisture it can hold – absolute humidity is particularly high in "laundry" climates. (See section 4.5 for notes on relative humidity and condensation.)
The humidity is given out by absorbent (hygroscopic) materials. Even modern, highly-finished laminated fibreboard absorbs up to 15 % its weight in water (Fig. 4.6.1.1).

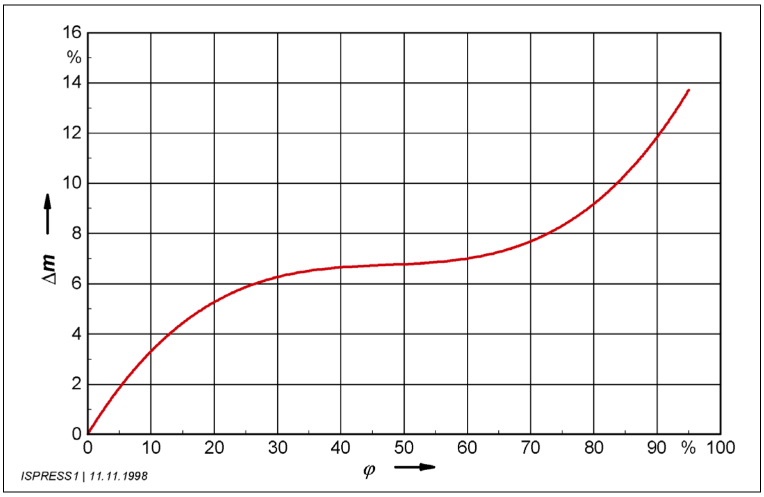


Fig. 4.6.1.1
Water absorption Δm as a percentage of the weight of the laminated fibreboard for storage in air at different relative humidities φ

If class A and E insulating materials (paper, laminated fibreboard, cotton, silk, asbestos) are used, prolonged exposure to high humidity causes a decrease in the material's insulating properties which can, in term, result in a failure of the winding. If one compares the breakdown strength of laminated fibreboard commonly used today and modern films, the basic difference becomes most noticeable if one looks at ***absolute level*** but is less clear as a function of the relative humidity (Fig. 4.6.1.2, note the logarithmic scale).

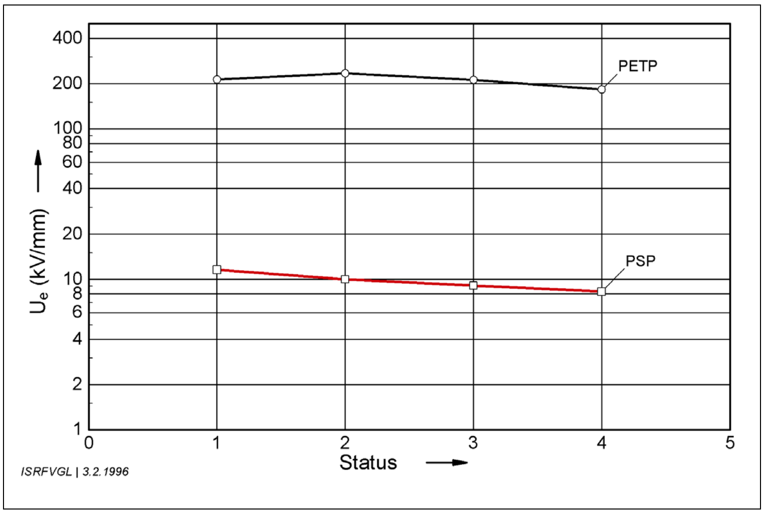


Fig. 4.6.1.2
Breakdown strength U_e of laminated fibreboard (PSP) and polyethylene terephthalate (PETP) film as a function of the relative humidity (RH)

Status:
1 Drying for 2 hours at 105 °C
2 Storage for 4 days at 50 % RH
3 Storage for 4 days at 65 % RH
4 Storage for 4 days at 85 % RH

according to series of tests carried out by
A. KREMPEL Soehne GmbH

The action of humidity cannot be prevented by a high degree of IP protection because the moisture penetrates the enclosure together with the air and because even the highest IP code does not guarantee air-tightness. The standard for the “Specification for degrees of protection provided by enclosures (IP Code)”, EN 60529 / IEC 60529, is therefore determined expressly in clause 2, “Scope”."Measures to protect ... the machinery ... against external influences such as moisture ... are matters for the relevant product standard."
In plain language: **Protection against moisture cannot be achieved by a high degree of IP protection.**
Progress made in the insulation industry has either solved or alleviated the problem in a simple manner:
Modern ***insulating sheeting*** (such as polyester films, aromatic polyamides, polyimide) are practically totally ***non-hygroscopic*** and offer a very high degree of ***protection against high humidity*** when combined with standard insulating systems.

4.6.2 Tropics

The standards have neither a unified definition of the zone covered by the “tropics”, nor a specification of the requirements on “tropical safety”, “tropical protection” or “tropical insulation”.
The terms are used interchangeably by different manufacturers by sometimes indicate different special measures depending on the status of the basic model.
The following explanations have been provided to clarify the terms, however, the list does not claim to be complete.
The section highlighted in Table 4.6.2.1 can be added to the tropics classified under ***open air climates*** in accordance with IEC 60721-2-1 [1.4]. The standard includes a world map on which the climatic zones have been highlighted in colour.

Table 4.6.2.1

Open air climates IEC 721-2-1

Designation	
EC	extremely cold
C	cold
CT	cold temperate
WT	warm temperate
WDr	warm dry
MWDr	mild warm dry
EWDr	extremely warm dry
WDa	warm damp
WDaE	warm damp equable

The following extracts have been taken from the excellent paper [3.1] to provide a more detailed explanation:
The tropics are zones of the earth in which ***constantly high temperatures*** prevail throughout the day, frequently combined **with *high levels of precipitation***. These zones experience no or little seasonal variation. The tropics are generally understood to be mainly those zones with a tropical climate but definitions of a tropical climate vary greatly:

- ☐ 20 °C isotherm in the coldest month,
- ☐ northern and southern limits of the trade winds or palm trees,
- ☐ southern and northern limits of snow,
- ☐ the lines of latitude on which the annual temperature fluctuations are greater than the daily temperature fluctuations.

The climate in the tropics stretches from the muggy topical rain forests at the equator to the arid desert climates around the tropics of Cancer and Capricorn. There are also areas with climates which differ markedly from the average conditions for these latitudes due to their high altitude, for example the solar radiation and atmospheric pressure or the ice and snow on mountain tops. The ambient conditions in some regions of the tropics are characterized by uniform conditions, while other regions are subject to extreme influencing factors.

Equable conditions:

- ☐ ***Temperature fluctuations****:* minimal daily and seasonal temperature fluctuations, sometimes less than 1 °K or no more than 6 °K.
- ☐ ***Day lengths***: average between 10.5 and 13.5 hours.
- ☐ ***Solar radiation****:* uniform.

Extreme conditions:

- ☐ ***Precipitation****:* showers throughout the year near the equator; showers during certain periods of the year near the Tropics of Cancer and Capricorn.
- ☐ ***Tropical storms in maritime regions****:* wind speeds of 100 km/h (60 mph) gusting at over 200 km/h (120 mph), for example the typhoons in the West Pacific and the hurricanes in the Caribbean.

The **main *environmental influences*** affecting electrical equipment in the tropics are:

- ☐ temperature and humidity
- ☐ storms and precipitation
- ☐ condensation and radiation.

Additional climatic conditions should also be noted:

- ☐ corrosive atmosphere near the sea due to the salt content of the air (Fig. 4.6.2.2),
- ☐ atmospheric discharges (lightning) in tropical storms
- ☐ sandstorms in deserts.

Bild 4.6.2.2
Conveyor line made up of mobile belt conveyors with drum rotors for salt extraction in a tropical region

4.6.3 Mould

Mould grows in all humid climates in still air conditions if temperatures are suitable and given the correct culture medium. Mould thrives in the 25 to 30 °C temperature range when combined with high relative humidity.
Mould may cause the following problems: Accumulation of moisture, discoloration of surfaces, corrosion, rotting and degradation of plastics, reduction in insulating properties and creapage paths.
Materials favoured by mould (such as leather, cardboard, animal and vegetable fats) should not be used in electrical machinery and equipment. It is better to use materials which provide no nourishment for the mould (such as silicone, plasticized PVC).

4.6.4 Termites

There are approximately 2000 known species of termite; about 500 of these should be regarded as harmful (Fig. 4.6.4.1). They are mainly found in the tropics. Termites will gnaw through anything which stands between them and their food if the material is softer than their jaws and its shape allows it to be grasped by their jaws. Wood, plastics and metals or other materials that can gouged with the finger nail are at risk.

Technical materials, such as plastics or drive timber, are only usually attacked by termites if their natural food runs out. The best living conditions for tropical termites are temperatures between 26 and 30 °C and a relative humidity of 90 to 97 **%.**

The best protection against termites is given by a ***metallic casing*** with a high degree of IP protection, i.e. at least IP5X, as used today for nearly all three-phase standard motors. The closure must be metallic or, in the case of shaft seals, for example, have a gap width of less than approximately 1 mm (Fig. 4.6.4.2). Plastic or rubber seals should not be accessible. Of course, this also applies to connecting leads and auxiliary leads. These should take the form of metal-armoured cables or metallic conduit.

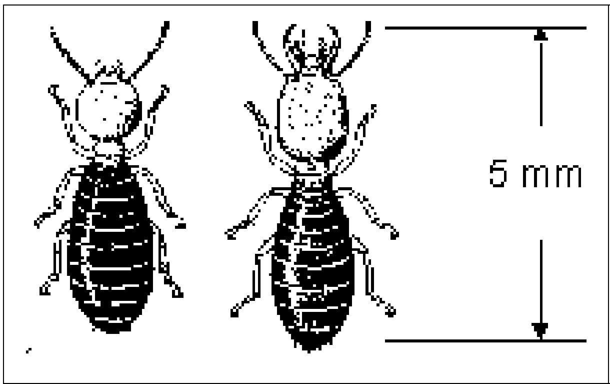


Fig. 4.6.4.1
One of the many species of termite
Left, a worker termite, right, a soldier termite

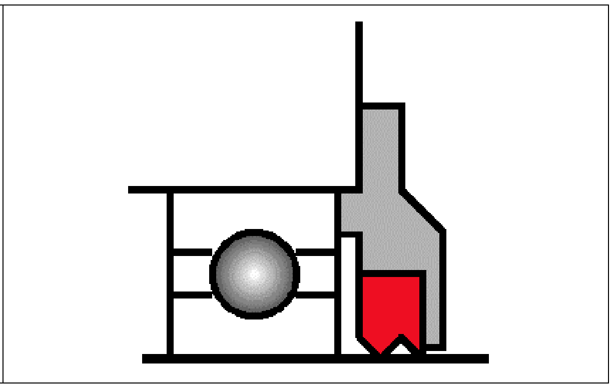


Fig 4.6.4.2
Shaft seal with metallic guard on neoprene parts

4.7 Outdoor installation

The term “outdoor installation” does not appear in the standards for the IP code and no degrees of IP protection or environmental conditions are assigned.
A brief explanation of the reasons for this discussed extensively in the standards committees follows.

4.7.1 References in the degree of IP standards

If one compares typical ***rainfalls*** with the ***severities*** determined for the IP tests, at first glance it would seem that the normal demands created by natural rainfall in our latitudes can be covered by degrees of IP protection (Table 4.7.1.1).

Table 4.7.1.1 Typical rainfalls in accordance with IEC 60721-2-2 [1.5]

Designation	Precipitation mm/h
Drizzle	< 1
Light rain	1
Moderate rain	4
Intensive rain	15
Heavy rain	40
Clousburst	> 100
Degrees of IP protection	
IPX1 test	60 (= 1 mm/min)
IPX2 test	180 (= 3 mm/min)

One should bear in mind that the standardized IP test lasts for 10 min but there are 8760 hours in a year.
The IP test cannot simulate long-term outdoor installation, even if the volume of water is increased. This requires special long-term testing or calls up the particular experiences of the manufacturer (Fig. 4.7.1.2).

Fig. 4.7.1.2
Long-term exposure of geared motors to rain to test fitness for outdoor installation

The sole reference to outdoor installation is made in the concept ***weather-protected*** *machines* in EN 60034-5 / IEC 60034-5. Clause 10. This standard makes it clear that degree of protection W is intended for a specific design of ***open-circuit air-cooled*** machines and as such is not applicable to closed, surface-cooled machines.
There are other good reasons for the standard's reticence:
When viewed globally, "outdoor installation" can entail extreme cold, extreme air temperatures, heating by solar radiation, high humidity, mould, corrosion and much more besides. Even in our moderate climate, additional demands can be placed on machinery operating in a sewage works or in an outdoor facility of a chemical plant, for example. These demands are not covered by the sweeping term "outdoor installation".
The "Scope" clause of the applicable standards on degrees of protection exclude the following influences ***from their field of application*** with good reason, even though they are relevant in this context:

- ☐ Corrosion
- ☐ Fungus
- ☐ Vermin
- ☐ Solar radiation
- ☐ Icing
- ☐ Moisture (e.g. produced by condensation).

The standards cannot, therefore, be used to determine the measures to be taken to equip an electrical machine for outdoor installation. The manufacturer must be consulted if information on this is not provided in the catalogue or operating instructions.

4.7.2 References in the installation codes of practice

The situation described by the installation codes specified in DIN VDE 0100 is somewhat different:
Part 737, "Humid and wet areas and rooms; outdoor installations", clause 5.2 states: "Machinery in unprotected outdoor installations must be protected against spray water at least IPX3."
One should note the following about this statement:

- This is a ***minimum requirement****.*
- The installation codes are directed primarily at the *safety* of persons and property. The maintenance of the ***functions*** of a machine ***used under special conditions*** is still governed by an agreement reached between the manufacturer and customer.

The ***standard*** *DIN VDE 0100 - 510* has the following field of application:
"510.1 This section is concerned with the selection of the machinery and its installation. The effectiveness of the protective measures and the observance of the requirements in respect of the satisfactory operation of the machine when used as designated and in respect of the external influences to be expected shall be ensured."

The standard lists in an 8-page annex the "external influences" to be observed in the selection of machinery. This provides a list of environmental influences rather than the sweeping term "outdoor installation" (Table 4.7.2.1). Only the "occurrence of water" or the "occurrence of solid foreign objects or dust in significant quantities" is referred to in a degree of IP protection as a "typical property" in terms of the selection of machinery (Table 4.7.2.2). All other influences must be accounted for by "appropriate design or execution".

Table 4.7.2.1 Assignment of climatic ambient conditions and the selection of electrical apparatus in accordance with DIN VDE 0100-510 : 1997; Table 51 A

Code	Air temperature in °C		Relative humidity in %		Selection
	Low	High	Low	hoch	
AB1	-60	+5	3	100	speziell
AB2	-40	+5	10	100	speziell
AB3	-25	+5	10	100	speziell
AB4	-5	+40	5	95	normal
AB5	+5	+40	5	85	speziell
AB6	+5	+60	10	100	speziell
AB7	-25	+55	10	100	speziell
AB8	-50	+40	15	100	speziell

Tabelle 4.7.2.2
Assignment of the occurrence of water and foreign objects in the selection of electrical apparatus in accordance with DIN VDE 0100-510 : 1997; Table 51 A

Code	External influences	Selection of machinery
	Water	
AD1	Negligible	IPX0
AD2	Dripping water	IPX1
AD3	Spraying water	IPX3
AD4	Splashing water	IPX4
AD5	Water jets	IPX5
AD6	Deckwater	IPX6
AD7	Immersion	IPX7
AD8	Submersion	IPX8
	Solid foreign objects (dust)	
AE1	Negligible	IP0X
AE2	Small (< 2.5 mm)	IP3X
AE3	Very small (< 1 mm)	IP4X
AE4	Light dust, low quantity	IP5X if no hazardous for the function of the apparatus
AE5	Moderate volume of dust	IP6X if there must be no dust penetration into the apparatus
AE6	Significant volume of dust	IP6X

Following on from the work of TC 75 of the IEC, all the standards in the IEC 60721 series, “Classification of environmental conditions”, have been under revision for several years.The aim is to classify both the requirements on electrical apparatus and the suitability for all types of environmental conditions by means of abbreviations. The system is just as complex and complicated as the natural conditions being standardized.

4.7.3 Differences in the type of electrical apparatus

The various types of electrical Thermal classification react in different ways to the demands of outdoor installation. This should become clear from the example of an electric motor.
In the case of *cage motors*, corrosion generally leads to deterioration in the motor's appearance, but ***not* to *failure of function*** (Fig. 4.7.3). The rolling contact bearings are sufficiently preserved by the grease, the air gap is not usually “blocked”, modern insulating materials are not hygroscopic and so are not susceptible.

Fig. 4.7.3
Drum motor on a portable belt conveyor operating in arduous conditions on a construction site

The situation is different for ***mechanical brakes*** often fitted on electric motors. Frictional material and metallic mating surfaces may “bake together”, particularly when the motor is at standstill. Furthermore, certain components of the frictional material can aggravate corrosion. Even though the motor's run-up is impaired, it should nevertheless be protected against failure by the necessary protective device.
Although corrosion between the friction lining and mating surface can be retarded and minimized, it can never be eliminated entirely. A sealed enclosure protects against water but not against moisture which can trigger corrosion.
As experience in this field clearly shows, some manufacturers offer specially designed brakes with ***rustproof friction surfaces***.

4.8 Impact, vibration, shock

Mechanical damage caused by external influences and not the electrical machine itself are relatively common. Certain fields of application – mining, woodworking, construction sites – place particularly high demands on motors. The conditions of operation are frequently described as “normal” but the process hides the true nature of the situation: A machine tool does not in itself represent an arduous application but a motor installed in an exposed location can easily be crushed by a forklift truck.
This section discusses several types of mechanical demand and in relation to the limits set in standards or codes of practice.

4.8.1 Impact

There are no limit values set in the standards for the demands of mechanical impacts encountered in standard industrial applications. Occasionally a correlation is drawn with the degrees of IP protection which is not strictly justified.
The “Scope” clause of EN 60529 / IEC 60529 states: "This standard deals only with enclosures which are in all other respects suitable for their intended use as specified in the relevant product standard and which from the point of view of material and workmanship ensure that the claimed degrees of protection are maintained under the normal conditions of use."
The minimum requirements on and tests for the ***impact resistance*** of enclosures are not a component of the IP Code. If a specification of this type is required to guarantee safety, the standards specific to the product must be supplemented and observed, as has been tried in EN 50014 / IEC 60079-0 (subclause 23.4.3.1), for example. Here the impact resistance requirements are specified as in Table 4.8.1.

Table 4.8.1 Impact test for explosion-proof electrical apparatus to EN 50014 / IEC 60079-0

<table>
<tr><td>Group</td><td colspan="2">I</td><td colspan="2">II</td></tr>
<tr><td>Zone</td><td colspan="2">Firedamp atmosphere
below ground</td><td colspan="2">Potentially explosive
atmosphere
above ground</td></tr>
<tr><td>Mechanical danger</td><td>High</td><td>Low</td><td>High</td><td>Low</td></tr>
<tr><td>Impact energy (in J oder W)</td><td>20</td><td colspan="2">7</td><td>4</td></tr>
</table>

Equipment with type of protection “e” (increased safety) derived in part from the normal series must, as a consequence, be able to withstand an impact test of 7 J. Figures 4.8.1.2 and 4.8.1.3 show designs for fan cowls before and after reinforcement by increasing the sheet thickness from 1.0 to 1.5 mm as necessitated by the introduction of this standard (1978).

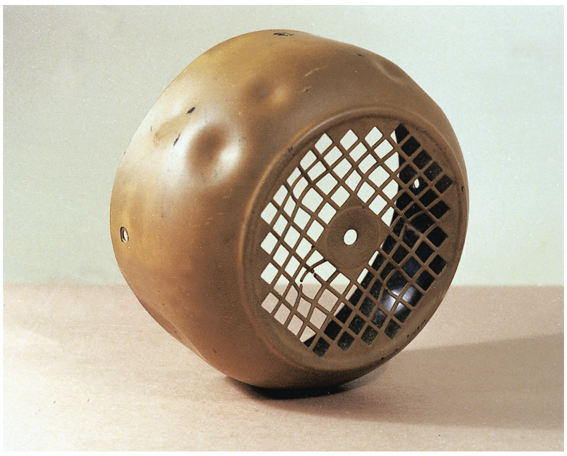


Fig 4.8.1.2
Unreinforced fan cowl after the impact test

Fig 4.8.1.3
Reinforced fan cowl after the impact test

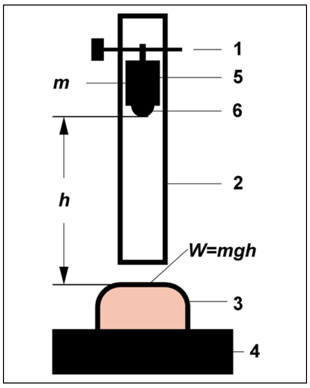


Fig. 4.8.1.4
Sheme of an impact test on the fan cowl of an electric motor using an impact energy of 7 J, for example, a striker of 1 kg falls twice from a height of 0.7 m
1 Height adjustment
2 Guide tube
3 Test specimen
4 Steel base ($m \geq 20$ kg)
5 Mass (e.g. $m = 1$ kg) in steel
6 Impact head 25 mm diameter, hardened steel
h Height of fall (e.g. 0.7 m)

Two further test devices have been standardized in addition to the impact test described in EN 50014 / IEC 60079-0, (Fig. 4.8.1.4).The instruments are manufactured by PTL, 95346 Stadtsteinach, Germany. A new classification system, the ***IK code***, was introduced in EN 61102 / IEC 61032 [1.21]. This is shown in Fig. 4.8.1.5 to clarify the orders of magnitude.

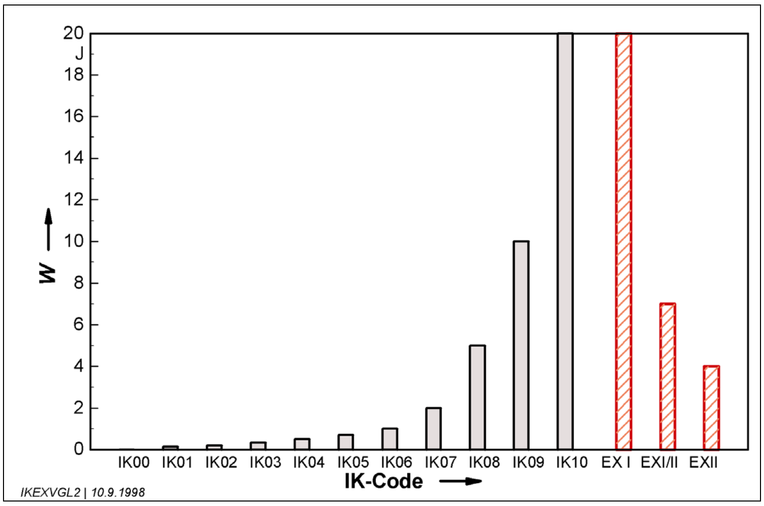


Fig. 4.8.1.5
Classification of the mechanical impact resistance using the IK Code in accordance with EN 61032 / IEC 61032 in comparison to the specifications for explosion-proof apparatus (EX)

Consequences for the user:
Electrical apparatus (motors, switchgear and control units) should be arranged as far as possible such that they are protected against the mechanical influences to be expected from use in accordance with the intended purpose. An additional cover can sometimes be more effective and cost-efficient than creating a special design for the apparatus (Fig. 4.8.1.6).

Fig. 4.8.1.6
Roller table drives on a cooling bank protected by a cover against mechanical damage caused by the red-hot material being conveyed

4.8.2 Vibration

Mechanical vibration cannot be entirely eliminated. If permissible limit values are exceeded, vibration can lead to malfunctions with considerable consequential damage:

- ☐ Mountings working loose ⇒ Scraping on rotating parts
- ☐ Rolling contact bearing damage ⇒ Scraping on the rotor
- ☐ Insulation damage ⇒ Winding failure
- ☐ Poor contact ⇒ Defective terminals or winding.

VDI Code of Practice 2056 is recognised internationally and adopts *vibration severity* as the measurement of vibration levels. This corresponds to the effective value of the ***speed of vibration***. The Code of Practice deals primarily with the ***emission*** (output) of vibrations. As there are no universally-recognised standards or codes of practice specific to electrical machines for permissible levels of ***immission*** (action), VDI Code of Practice 2056 can also be used as a guide for the permissible vibrational stress.

Machines are categorized into groups K, M, G, T, D, and S. Of these, the following are of most significance for electrical machines:

Group K: of particular significance for mass-produced electric motors up to approximately 15 kW,

Group M: of particular significance for electric motors with a power rating of 15 to 75 kW.

The rating limits for these machine groups are shown in two diagrams as a simplied extract of the whole in Fig. 4.8.2.1. Here:

s_{max} Displacement (half-wave peak value)

n Speed of rotation

v_{eff} Effective speed of vibration (velocity)

1 Range below the average threshold of human perception

2 “Good” range

3 “Acceptable” range

4 “Permissible” range

5 “Impermissible” range

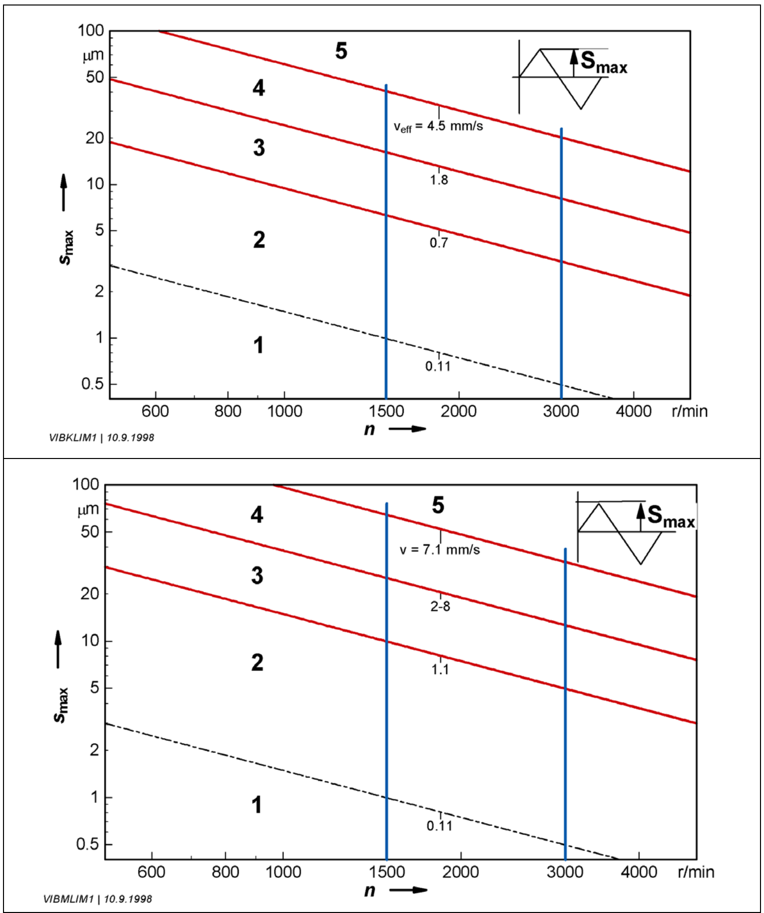


Fig. 4.8.2.1
Rating limits for the vibration levels in accordance with VDI 2056

a) Machine group K

b) Machine group M

Vibration severity can be measured on-site by relatively simple means. Measuring conditions and measuring points are specified in VDI 2056 and ISO 2373.
Fig. 4.8.2.2 provides a correlation between subjective perception and objective measured values and the rating limits:

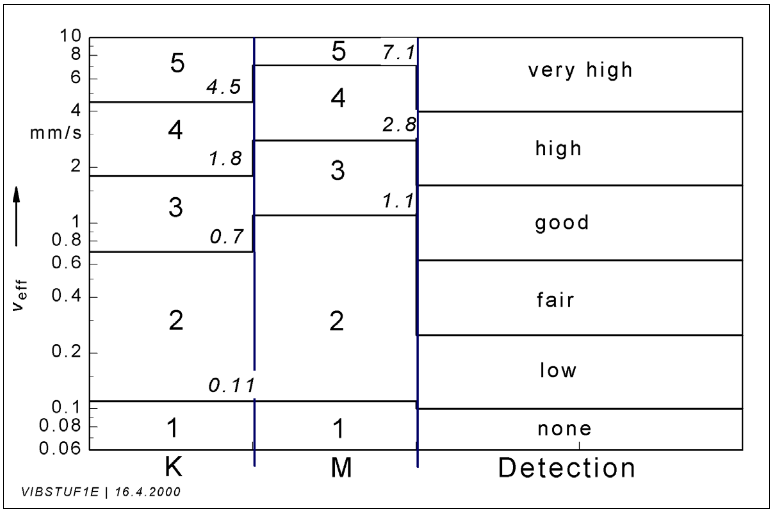


Fig 4.8.2.2
Correlation between subjective perception and the rating limits in accordance with VDI 2057

The FV1 safety data sheet issued by ZVEI, the "Zentralverband Elektrotechnik- und Elektronikindustrie e.V.", designates the following limits for the action of external vibrations in the vicinity of journals as *harmless*:

- ☐ Machine group K: $v_{eff} \leq 3.5$ mm/s during operation,
- ☐ Machine group M: $v_{eff} \leq 4.5$ mm/s during operation.
- ☐ All machine groups: $v_{eff} < 0.2$ mm/s during standstill,

EN 60034-14 / IEC 60034-14 [1.14] is not of interest in relation to the overall heading of “Special environmental conditions” since it specifies normal and special requirements on the ***balance quality*** of electrical machinery. It is mentioned here in brief for the sake of completeness.
The mechanical vibrations of rotating electrical machines are measured in accordance with this standard and three ***levels of vibration intensity*** are assigned. Table 4.8.2.3 shows the limit values for the effective value of the speed of vibration v_{eff} as a function of the shaft height *H*.

Tabelle 4.8.2.3
Speed of vibration of electrical machines in accordance with EN 60034-14 / IEC 60034-14

Vibration severity level	n_1 r/min	v_{eff} in mm/s for		
		$80 \leq H \leq 132$	$132 < H \leq 225$	$225 < H \leq 400$
N (normal)	600 to 3600	1.8	2,8	4,5
R (reduced)	600 to 1800	0.71	1,12	1,8
	> 1800 to 3600	1.12	1,8	2,8
S (special)	600 to 1800	0.45	0,71	1,12
	> 1800 to 3600	0.71	1,12	1,8

4.8.3 Shock

Shock is understood as the sudden violent movement of a mass. The process is not periodic and generates considerable forces on the masses (Fig. 4.8.3.1).

Shock loads may be caused, for example, by

- ☐ earthquakes,
- ☐ explosions,
- ☐ heavy waves (breakers) on ships,
- ☐ storms.

A shock is characterized by the ***maximum acceleration***, expressed as a multiple of the acceleration due to gravity a_{max}/g.

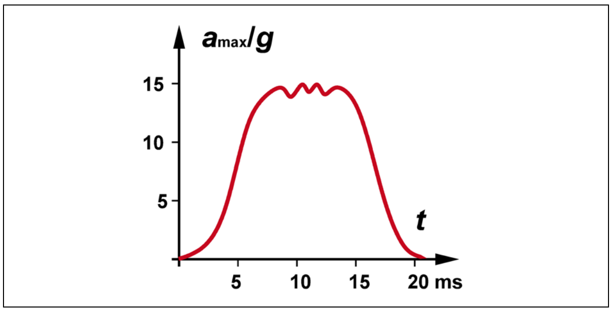


Fig. 4.8.3.1
Typical pattern of a shock
Acceleration as a multiple of acceleration due to gravity a_{max}/g over time t

Limit values

There are numerous specifications for the *shock resistance* of electrical machines used in military applications whereas regulations for use in industrial applications are rare. Fig. 4.8.3.2 is based on data provided by LOHER; the values do not contain any additional safety factors. The manufacturer must be consulted before these guide values are adopted.

The marked decrease in the permissible acceleration as the overall dimensions increase can be explained by the familiar relationship

$$\boldsymbol{F = m \cdot a}$$

The forces F grow in relation to the mass m to be accelerated which, in turn, increases super-proportionally in relation to the shaft height (overall dimension) of a motor (Fig. 4.8.3.3).

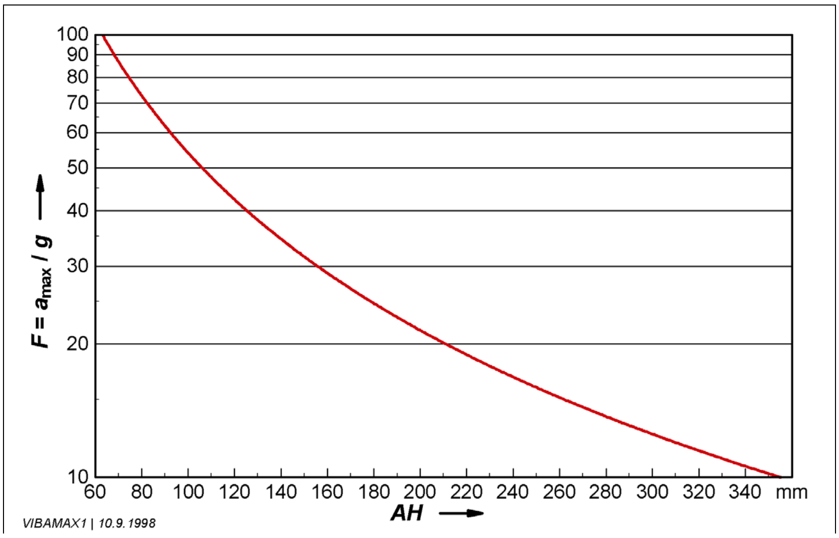


Fig 4.8.3.2
Permissible shock as a multiple of the acceleration due to gravity a_{max} / g for electrical machines as a function the shaft height AH

LOHER catalogue data

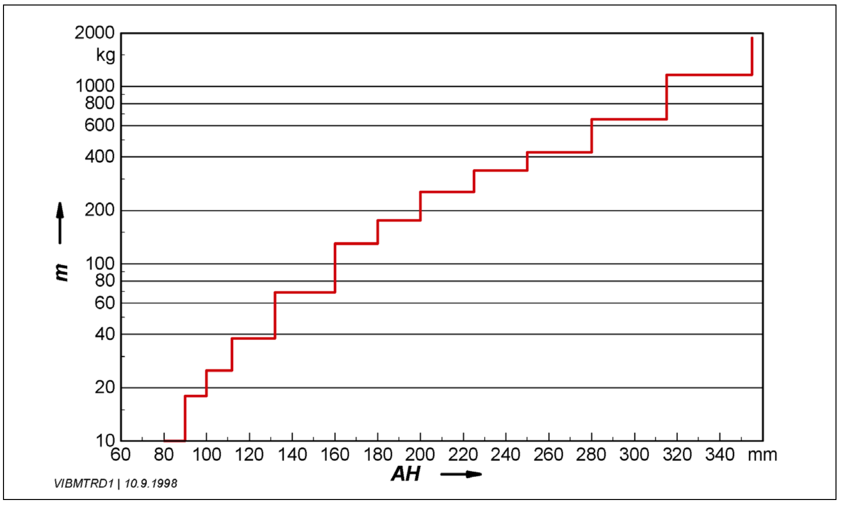


Bild 4.8.3.3
Super-proportional increase in mass *m* of standard motors with shaft height *AH*

Classes and safety levels for shock resistance
Machinery to be used in shelters for the purpose of civil protection must undergo shock resistance testing. The degree of resistance is categorized into five ***classes (RKs)*** and in three ***safety levels***. The values in Table 4.8.3.4 are intended to provide an overview of the orders of magnitude of a shock.

Table 4.8.3.4 Shock resistance classes

Class	Principal characteristic values		Secondary characteristic values	
	Maximum speed v_{max} m/s	Maximum acceleration a_{max} m/s²	Maximum displacement s_{max} cm	Acceleration increase (jerk) r_{max} g/ms
RK 0.63 / 6.3	0.63	6.3 g	10	1,6
RK 1.0 / 10	1.0	10 g	16	2,5
RK 1.6 / 16	1.6	16 g	25	4,0
RK 2.5 / 25	2.5	25 g	40	6,3
RK 4.0 / 40	4.0	40 g	63	10

g = 9,81 m/s² Acceleration due to gravity

The machinery's intended use plays an important role in classification into ***safety levels***: A fan drive supplying a shelter with oxygen would be adequate if, for example it meets the requirements of safety level B, i.e. it fails only for the duration of the shock (caused, for example, by the brushes lifting off in the case of a battery-fed D.C. motor) (Fig. 4.8.3.5).

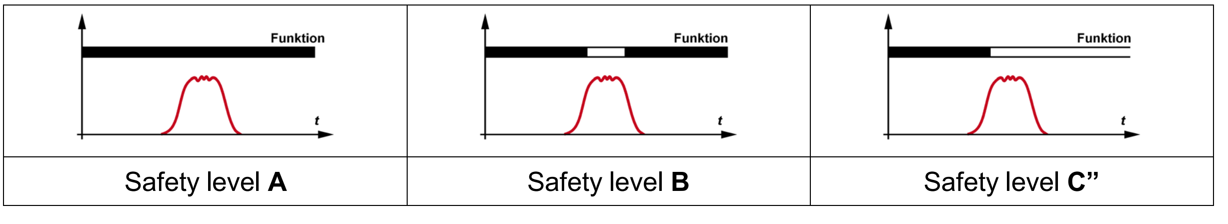


Fig. 4.8.3.5 Shock resistance safety levels
Safety level A Function ensured during and after the action of the shock
Safety level B Function impaired during the action of the shock, thereafter function shall be ensured
Safety level C Function failure shall not cause consequential damage.

4.9 Explosion protection

Many of the protective measures touched upon in this book form part of a type of protection the observance of which is a legal requirement. Full detail on explosion protection are provided in [2.21].

5 Types of motor overload

Three-phase cage motors may undergo relatively high levels of overloading for short periods. The minimum values are stated in [1.6].

Occasional current overloading
The current overload capacity of rotating machines is specified so that control and protection devices can be configured for the machine. Tests to determine overload capacity are not required by this standard.
An approximate calculation of the degree of heating of the motor's windings is obtained by multiplying the time by the square of the current. Overcurrent causes increases in temperature. Unless otherwise agreed, it may be assumed that the machine will only be operated at the overcurrents stated for few brief periods over its entire service life.
Three-phase motors (except commutator motors) with rated outputs up to 315 kW and rated voltages up to 1 kV must be able to withstand a current equal to 1.5 times the rated current for at least 2 minutes.

Short-term torque overloading of polyphase induction motors
Regardless of their operation or design, motors must be able to withstand overloading of up to 1.6 times the rated torque for 15 seconds at their rated voltage and also, in the case of induction motors, at their rated frequency without experiencing a sudden retardation of speed (with a gradual increase in torque).

Some of the causes of overloading on drives are described in the following sections.

5.1 Driven machinery

Most driven machinery can be overloaded, particularly when operated manually, and then place greater demands on the drive.

5.1.1 Increased power consumption
It may be assumed that every motor manufacturer produces ***load characteristics*** or ***operating characteristics*** similar to Fig. 5.1.1 as part of type testing.

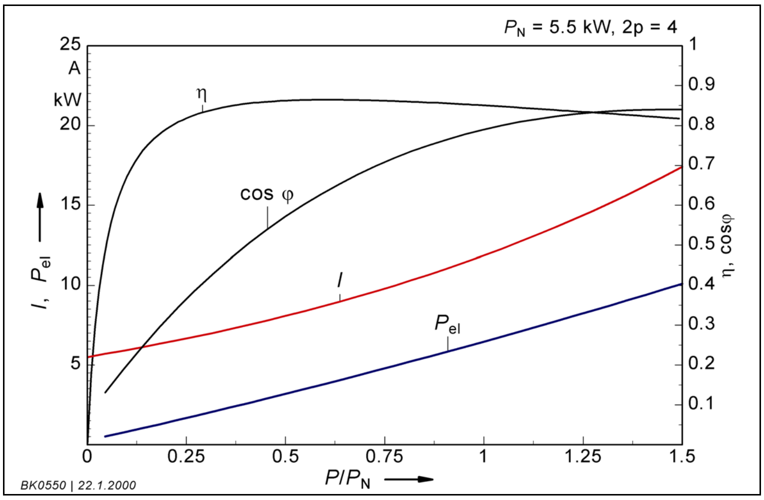


Fig. 5.1.1
Typical load characteristics of a 4-pole three-phase asynchronous motor, rated output 5.5 kW

Characteristics of this type have been plotted by the manufacturer using a precisely controlled rated voltage. They are only meaningful in the determination of the actual output based on the measurement of the current consumption if the rated voltage (across the motor's terminals!) deviates only slightly from the setpoint value when the measurements are conducted at the site of use. Tolerances of approximately ± 3 % appear to be permissible in this context.

The permissible voltage fluctuations of ± 5 % in “zone A” or ±10 % in “zone B” quoted in EN 60034-1 / IEC 60034-1, subclause 12.3 relate to the function of the motor only and not to the often considerable influence on the shape of the current characteristic curve which is, in fact, decisive in the calculation of the output.
Load characteristics of the type shown are generally available from the manufacturers of mass-produced motors (standard motors). When requesting this information, please quote the ***serial number*** of the motor in question as motors are often manufactured with different winding designs under the same type designation and this will have an effect on the load characteristics.
Motors with a rated output of less than approximately 1 kW require a relatively high magnetizing current; the current characteristic curve is therefore very flat (Fig. 5.1.2). Due to the high magnetic saturation, a large scatter band is also produced, the size of which depends on the actual mains voltage applied; this may deviate ± 10 % from the rated value in accordance with the standards for the mains power supply (IEC 60038). The current consumption is representative of the ***thermal loading*** of the winding; current-dependent overload protection devices (e.g. bimetal relays) are able to function. However, the current consumption on motors of this type is relatively meaningless in terms of the ***actual output***. The electrical power consumption serves as the metric in this instance: As you will notice from Fig. 5.1.3, the electrical power consumption has a relatively steep curve, even for small motors, and so provides a good means of analysis.

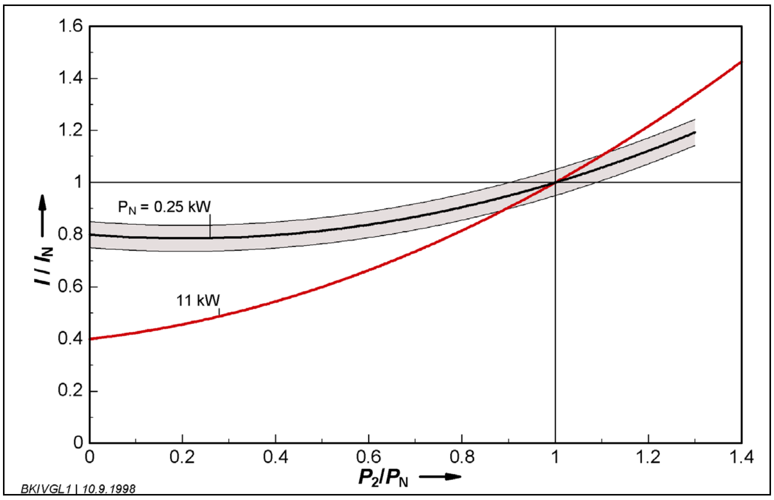


Fig. 5.1.2
Relative current consumption I/I_N as a function of the relative load P_2/P_N for three-phase cage motors with a rated output P_N = 0.25 and 11 kW

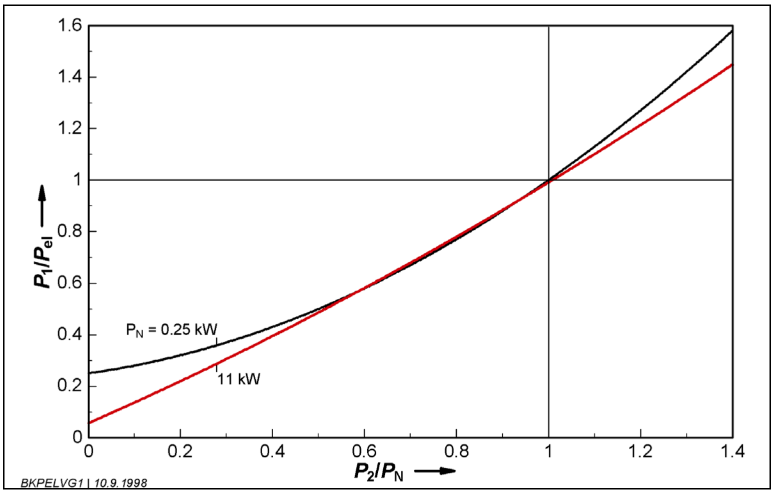


Fig. 5.1.3
Relative input (power) P_1/P_{el} as a function of the relative loading P_2/P_N for three-phase cage motors with a rated output P_N = 0.25 and 11 kW

5.1.2 Blockage

The torque requirement on some types of drive can rise above the breakaway torque or pull-out torque developed by the motor so the motor is blocked. Electrical engineers term the operational status in which the rotor has locked as ***"short-circuiting of the motor".***

The duty type of a motor gives rise to special requirements on the overload protection. Let us consider a digger (Fig. 5.1.2.1**)** denstrate this point:

When the motor is switched on with the shovel out of the material (sand, gravel, hardcore), the motor draws the starting current I_A, then moves the shovel under virtually no load (I_0) until it makes contact with the material. The load current I_L increases as the shovel is filled until it reaches the ***rated current*** $\boldsymbol{I_N}$. If the shovel encounters unexpected and extremely high resistance (e.g. a large lump of stone), the motor may stall and draw the ***starting current (locked rotor current)*** $\boldsymbol{I_A}$.

The current alters in the ratio $I_0 : I_A$, i.e. 1 : 12 under a typical cycle.

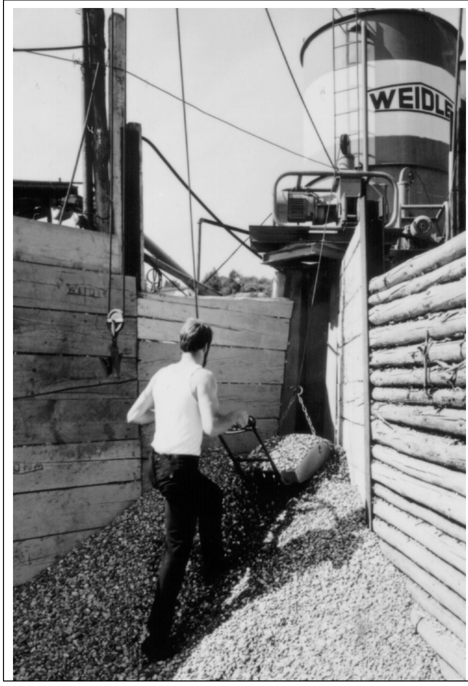


Fig. 5.1.2.1

Digger as an example an electric motor with a varying load during a working cycle

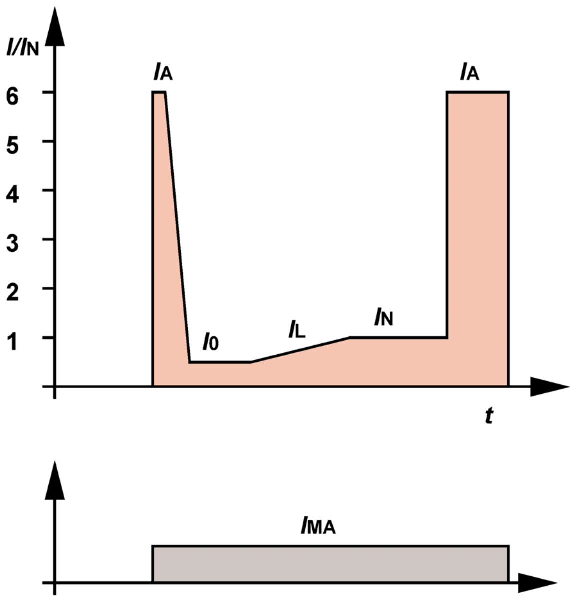


Fig. 5.1.2.2

Current consumption during the working cycle of a digger

I_A	Starting current under motor switch-on or locked rotor conditions
I_0	No-load current
I_L	Load current
I_N	Rated current

The thermal effects of different load conditions is shown clearly in Fig. 5.1.2.3; it is assumed that the current (I_A, I_0, I_N) specified in each case flows at a constant level. The currents for the example selected in Fig. 5.1.2.3 are in a ratio of approximately $I_0 : I_N : I_A = 0.6 : 1 : 4$; the degrees of heating are approximately 0.35 : 1 : 15. In the case of the digger shown in Figures 5.1.2.1 and 5.1.2.2, the temperature would rise so quickly in the event of a blockage at I_A that it would no longer be possible to display it using the plotting scale selected here.

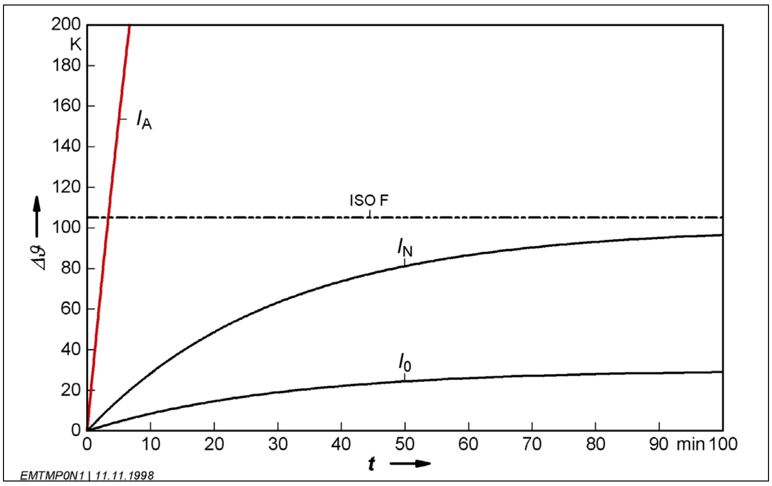


Fig. 5.1.2.3
Temperature increase $\Delta\vartheta$ under no-load (I_0), nominal load (I_N) and with locked rotor (I_A) in comparison to the critical values for temperature class F (ISO F)

The torque-speed relationship of a cage motor is shown in Fig. 5.1.2.4: As the relative load M/M_N increases, the speed decreases linearly by approximately the degree of slip; when loaded with the pull-out torque M_K the motor is stalled and is stationary with rotor locked while the breakaway torque M_A is developed.

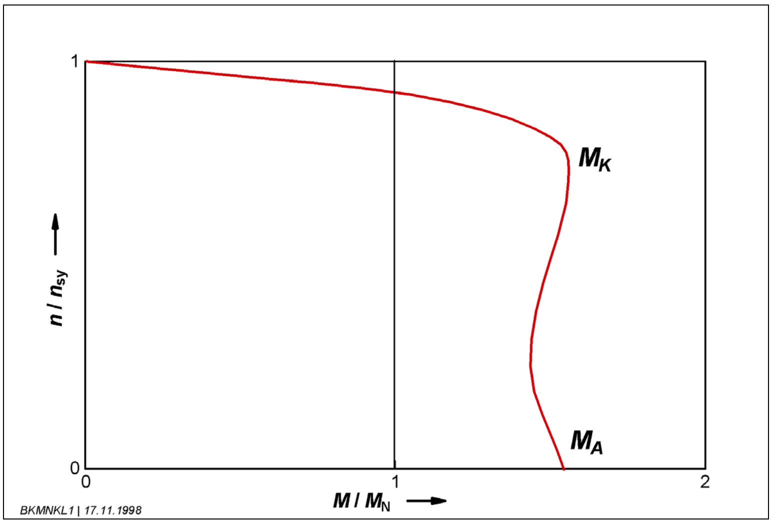


Fig. 5.1.2.4
Characteristic torque-speed graph of a cage motor
M/M_N Torque relative to the rated torque
n/n_{sy} Speed relative to the synchronous speed (e.g. 1500 r/min)
M_K Pull-out torque (breakdown torque)
M_A Breakaway torque (locked rotor or starting torque)

5.2 Mains

There is generally no risk to motors from the power supply provided by modern industrial mains. However, the situation may arise where the winding is endangered thermally (through long-term voltage deviation) or dielectrically (through voltage spikes).

5.2.1 Tolerances in accordance with the standards

5.2.1.1 Mains voltage in accordance with IEC 60038

Efforts to establish a worldwide standard voltage reached a preliminary conclusion in 1983 with IEC 60038. The identical German national standard DIN IEC 60038 appeared in 1987. The standard voltages used for 50 Hz supplies, i.e. 380, 415, 420 and 440 V, will be replaced by one standard voltage of 400 V over a transitional period estimated at 20 years. The corresponding value would then be 230 V for single-phase supplies.

Mains standard

The new rated values should be adopted by 2003. In fact, CENELEC Memorandum No. 14 recommended that the new rated voltages be introduced by 1993. However, because Great Britain (voltages of 415, 420 and 440 V) did not formally agree to this until 1993 and only began the process of conversion to the amendments made to the “Wire regulations”, BS 7671, introduced at the end of 1994, it has no been possible to achieve the actual goal of a *world standard voltage* at 50 Hz. A tolerance of +6 / –10 % will be applicable for the mains voltage until 2003; after this, a tolerance of ± 10 % will be applicable.

Significance of a voltage specification of 230 V

According to information from VDEW, three-phase supplies of are no longer found in the old Bundesländer. There are still a few 3 x 220 V three-phase supplies in the territory of the former German Democratic Republic; these will be converted to 3 x 400 V as soon as possible.

The 230 V voltage is nearly always a ***single-phase*** *voltage* for lighting and control mains. Therefore, a voltage specification of 230/400 V can be assumed to identify a supply system having 1~ 230 V / 3~ 400 V. The designation 230/400 V Δ/Y (that is 3~ 230 / 3~ 400 V Δ/Y) makes no sense for ordering and labelling motors supplied by the mains and should therefore be avoided. Only inverter-fed motors may be 3 x 230 V rated.

Acceptance of the “Euro voltage” in European countries

In spite of the CENELEC Memorandum, practical acceptance of the “Euro voltage” is generally found to be unsatisfactory, even though we are close to the end of the transitional period. This applies in particular to Great Britain whose special supply of 415 or 420 V was an important factor for the introduction of the new 400 V voltage (Fig. 5.2.1.1).

The survey does not make clear the proportion of motors to be used in the country concerned (i.e. at the “standardized” 400 V) and what proportion is intended for export to countries where the 380 V standard is still used.

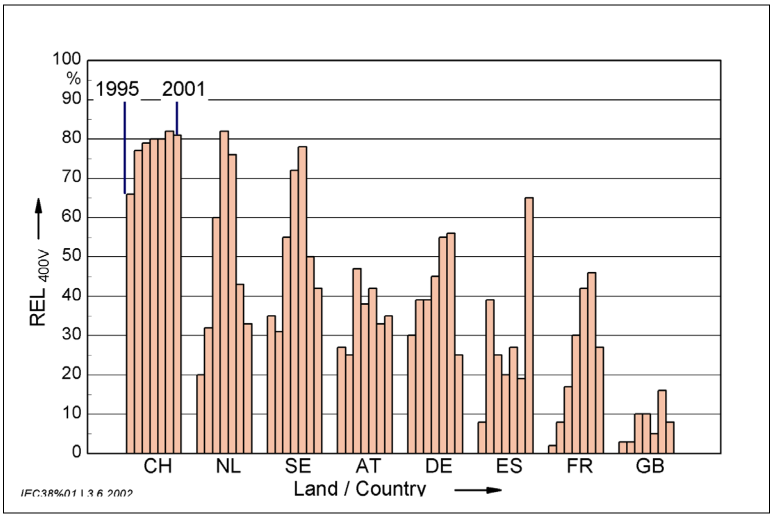


Fig. 5.2.1.1
Acceptance of the “400 V Euro voltage” in eight European countries

Source: Danfoss Bauer GmbH

5.2.1.2 Permissible voltage variations for electrical machines

EN 60034-1 which has been harmonized with IEC 60034-1, still applies to electrical machinery. Subclause 12.3 of this standard specifies a permissible voltage fluctuation of ± 5 %.
This tolerance relates to the particular voltage specified on the rating plate, i.e. a motor designated for

380 V	can be used for	361 to 399 V
400 V		380 to 420 V

The standardized tolerance of ±5 % is not specified on the rating plate (cf. subclause 12.3 in [1.6]).
In contrast to the specifications for the system voltage and tolerance of many other electrical apparatus, electrical machines allow a relatively tight supply voltage tolerance band. This is based on the following technical grounds: Small motors (e.g. below approximately 1.1 kW) and low-speed motors often operate near to the magnetic saturation and are relatively sensitive to overvoltage.
If the motor is being operated under voltage fluctuations which exceed the ± 5 % currently standardized, [1.6] specifies that the motors must be ***capable of performing their primary function***: They can deliver their rated torque. In this case, the usual characteristics (and the heating as well, for example) may exhibit greater deviation from the data specified for the rated voltage (**Fig. 5.2.1.2**).

	ΔU (%)	
	10	
	5	Zone B The motor shall be capable of performing its primary function but may exhibit greater deviations from its performance; extended operation at the perimiter of zone B is not recommended; not permissible for EEx e
Nominal working point or rated point	0	Zone A The motor must be capable of performing its primary function in continuous running duty The degree of heating may be 10 K higher than the limit value; also permissible for EEx
	- 5	
	- 10	Zone B The motor shall be capable of performing its primary function but may exhibit greater deviations from its performance; extended operation at the perimiter of zone B is not recommended; not permissible for EEx e

Fig. 5.2.1.2 Permissible voltage variations for motors
in accordance with EN 60034-1 / IEC 60034-1, Fig. 14

Tolerance zone B represents a concession for ***normal, non explosion-proof*** machines which manufacturers and operators may use at their own risk after weighing up the effects on the operating data and service life of the winding insulation. Because safety is affected in the case of ***explosion-proof*** motors, the conversion to a 400 V supply must be performed and documented in compliance with the relevant standards (e.g. EN 50018 and EN 50019) and the specific motor design.

5.2.2 Performance characteristics under voltage variation

A test series can be used to assess the performance characteristics of three-phase asynchronous motors under variation of the supply voltage. This is often performed as part of the type test to fine-tune the winding design: constant output at different voltages. Fundamentally, the type test is used to determine the ***magnetic flux density (induction)*** which gives the best performance characteristics. The winding is then designed for mass production such that the most favourable flux density is achieved when the motor is operated at the rated voltage. If at all possible, the flux density should be selected such that the least losses are experienced at the rated voltage. In this arrangement, motor heating is kept to a minimum at the rated output (hereafter termed the ***optimum flux density)***.
However, there are compelling reasons for selecting a flux density that is lower or higher than the optimum flux density.

The information in Figs 5.2.2.1 to 5.2.2.3 must be viewed as purely qualitative. The trend should be perfectly clear from a simplified and exaggerated presentation. This does not lend itself to quantitative analysis.

- ☐ The ***active current*** $\boldsymbol{I_w}$ – which contributes to the mechanical output – exhibits a falling trend (because of the slip decreasing, etc.) as the voltage (flux density) increases.
- ☐ The ***magnetizing current*** $\boldsymbol{I_\mu}$ – which forms the magnetic flux – exhibits a rising trend as the voltage (flux density) increases. This trend is super-proportionally steep, particularly when the saturation limit is reached.
- ☐ The ***line current I*** – to be measured in the supply line – is composed geometrically of the components Iw and I_μ.
- ☐ The ***minimum line current I*** – which also represents the losses – characterizes the optimum flux density.

Rated voltage (flux density) within the optimum flux density (Fig. 5.2.2.1)
This arrangement must be achieved if possible and is typical for motors with rated outputs of approximately 1.1 to 11 kW.

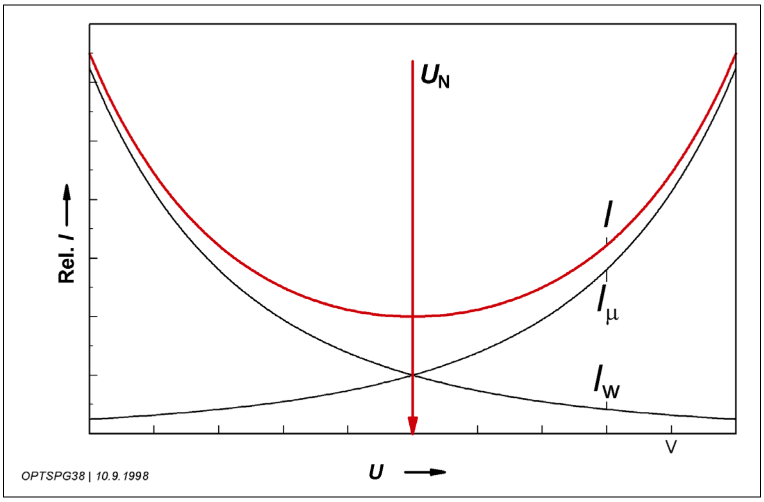


Fig. 5.2.2.1
Current consumption trend I of medium-size motors (approx. 1.1 to 11 kW) under variation of the supply voltage U

Rated voltage assignment U_N within the optimum flux density (qualitative representation)

Assessment of the performance characteristic:

- ☐ Voltage variations within standard tolerances have relatively little effect on the current consumption (heating).
- ☐ It is generally permissible to continue to operate a motor wound for 380 V at the new rated voltage of 400 V.

Rated voltage (flux density) below the optimum flux density (Fig. 5.2.2.2)
This arrangement is typical for motors with rated outputs above approximately 11 kW since excessive breakaway torques and starting currents would result at the optimum flux density. Although the breakaway torques only pose a danger to downstream transmission components (geared motors) and driven machinery, high short-circuit current densities lead to dangerously rapid and severe temperature increases in the event of stalling which may no longer be detected by thermistors etc.

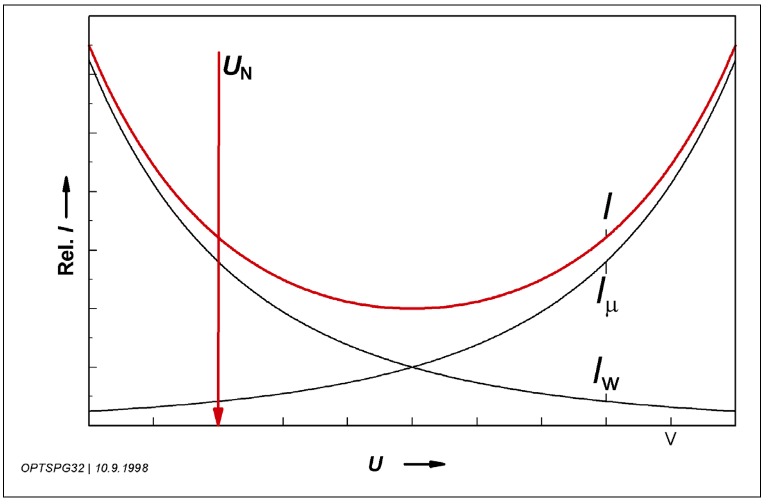


Fig. 5.2.2.2
Current consumption trend *I* of large motors (approx. > 11 kW) under variation of the supply voltage *U*

Rated voltage assignment U_N below the optimum flux density (qualitative representation

Assessment of the performance characteristic:

- A reduction in the voltage leads to increased current consumption (heating),
- An increase in the voltage leads to reduced current consumption (heating),
- Continued operation of a motor wound for 380 V at the new rated voltage of 400 V is permissible if the increased M_A and M_K values are harmless for the driven machinery.

Rated voltage (flux density) above the optimum flux density (Fig. 5.2.2.3)
This critical arrangement may be required for motors with rated outputs below approximately 1.1 kW because the standardized overload capacity $M_K/M_N \geq 1.6$ would not be achieved at the optimum flux density. This is the critical group when it comes to the continued operation of 380 V motors at the 400 V mains supply.

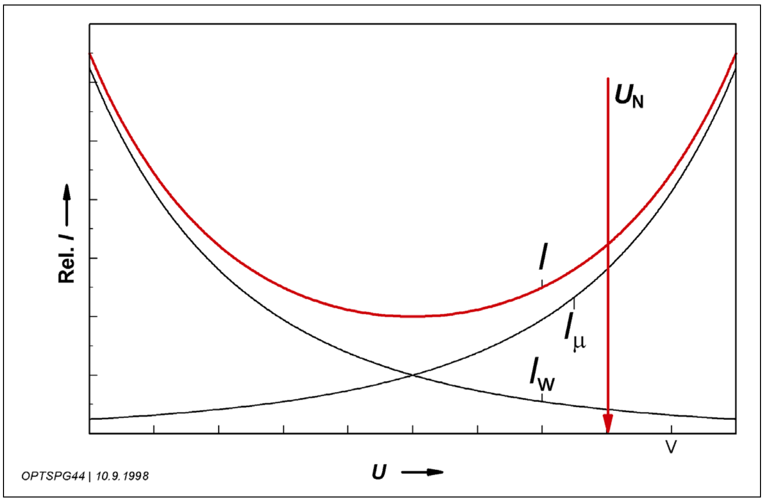


Fig. 5.2.2.3
Current consumption trend I of small motors (approximately < 1.1 kW) under variation of the supply voltage U

Rated voltage assignment U_N above the optimum flux density (qualitative representation)

Assessment of the performance characteristic:

- ☐ A reduction in the voltage leads to reduced current consumption (heating), but this jeopardizes the overload capacity $M_K/M_N \geq 1.6$ as required by the standard.
- ☐ An increase in the voltage leads to a considerable increase in the current consumption (heating) due to saturation. The no-load current may be greater than the rated current.
- ☐ The ability to continue to operate a 380 V motor at the new rated voltage of 400 V is generally uncertain. Check the current consumption and heat build-up in actual operation and consult the manufacturer.

5.2.3 Voltage spikes

Public mains supplies are generally free from voltage spikes which could jeopardize winding insulation in sensitive consumers (industrial electronics, computers). However, localized voltage spikes of a critical magnitude or frequency may be caused in industry by certain consumers; the following two examples serve to represent the many possible causes.

5.2.3.1 Self-inductance of a solenoid

When a solenoid is switched on, a cutoff voltage peak is generated from the energy of the magnetic field, the magnitude of which is determined by the cutoff speed.

$$e = -\frac{d\phi}{dt}$$

The oscillogram in Fig. 5.2.3.1.1shows a cutoff process of this type.

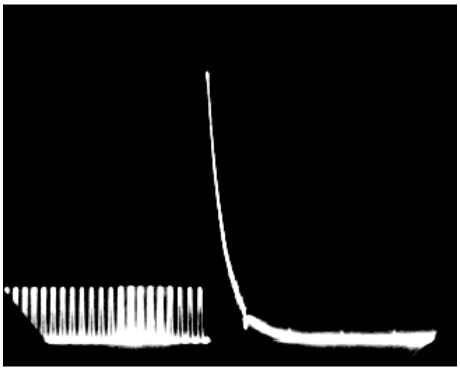


Fig. 5.2.3.1.1
Oscillogram of the cutoff voltage peak of a D.C. solenoid release

At worst, induction spikes of up to 20 times the rated voltage may be experienced when the power is switched off. It is therefore recommended that as low a rated voltage as possible be selected for the magnet (e.g. 24 V) so that the voltage spike (e.g. 480 V) remains within the breakdown strength of normal insulating materials. The voltage spikes may become dangerously high (e.g. 3600 V) at higher coil voltages (e.g. 180 V) and must be reduced by special protective circuitry with resistors, capacitors, selenium diodes, zener diodes or varistors (Fig. 5.2.3.1.2).

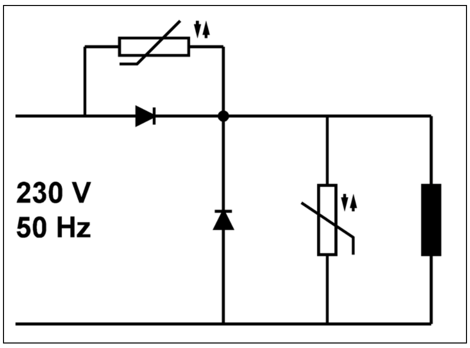


Fig. 5.2.3.1.2
Half-wave rectification with current feedback diode and protective circuitry provided by voltage-dependent resistors (varistors)

5.2.3.2 Switching voltage PWM converters

The approximation of the motor's current to the ideal sinus wave (Fig. 5.2.3.2.1) and the minimization of harmonic loss and noise have a technical price to pay:

Pulse frequencies in the ultrasonic range (≥ 16 kHz) require extremely fast semiconductor switches (e.g. IGBT = Insulated Gate Bipolar Transistor or MOS field-effect transistors) with switching times of less than 200 ns (1 nanoseconds = 10^{-9} seconds).

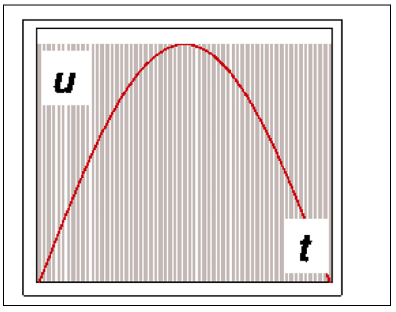


Fig. 5.2.3.2.1
General representation of the pulse-width modulation to generate a sinusoidal output voltage on the pulse-width modulation converter (pulse frequency: up to 20 kHz)

Table 5.2.3.2.2 serves to clarify the orders of magnitude compared with conventional mains supply processes.

Table 5.2.3.2.2 Typical ratings for converters

	Pulse frequency	Switching time	Rate of voltage rise
	Hz	s	V/µs
Converter	20 000	$100 \cdot 10^{-9}$	50 000
Mains	50	$5 \cdot 10^{-3}$	0.2
Relation	400	50.000	250 000

High rates of voltage over time ratios d*u*/d*t* and voltage spikes occur. These may rise to between 10 and 50 kV/µs and to double the intermediate circuit voltage (e.g. $2 \cdot \sqrt{2} \cdot 400$ V = 1100 V) (Fig. 5.2.3.2.3) in conjunction with long lines (e.g. > 25 m) and other unfavourable parameters due to reflexions and transient effects [3.7]

Values in the order of a 2.5-fold rise were recorded during a simulation of the voltage rise using an asymmetrical rectangular signal at the start and end of a 50 m line at a base frequency of 38.6 kHz (Fig. 5.2.3.2.4).

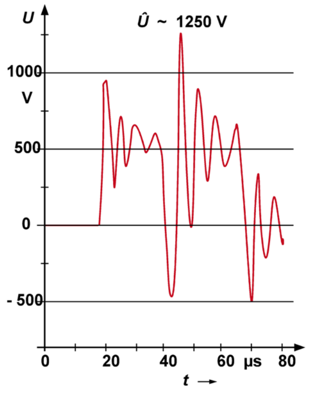


Fig. 5.2.3.2.3
Switching voltages measured across the motor terminals in the transient initial condition of a switch-on procedure [3.6]
Voltage peak value: approximately 1250 V

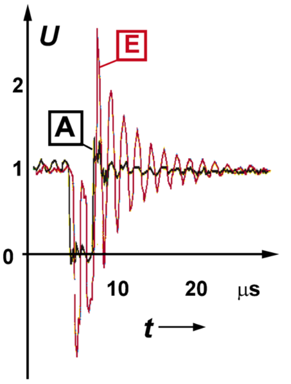


Fig. 5.2.3.2.4
Simulation of the voltage rise at the end (E) of a 50 m line over the start (A); base frequency: 38.6 kHz
Source: Annual Report of the PTB (Physikalisch-Technische Bundesanstalt) 1994

Loads are placed on the winding insulation comparable to the ***transient waves*** caused by lightning discharge – with the important difference that we are dealing here with a continuous load with a high pulse frequency and not an occasional, on-off occurrence.
The voltage across the winding alters so quickly that the potential at the start and end of a phase differs – in the worst case scenario of a parallel coil groups and a “wild” winding, the paint film between two adjacent wires is loaded with the full peak voltage.
The ***effect of the line length*** further aggravates the situation, as shown in Fig. 5.2.3.2.5.

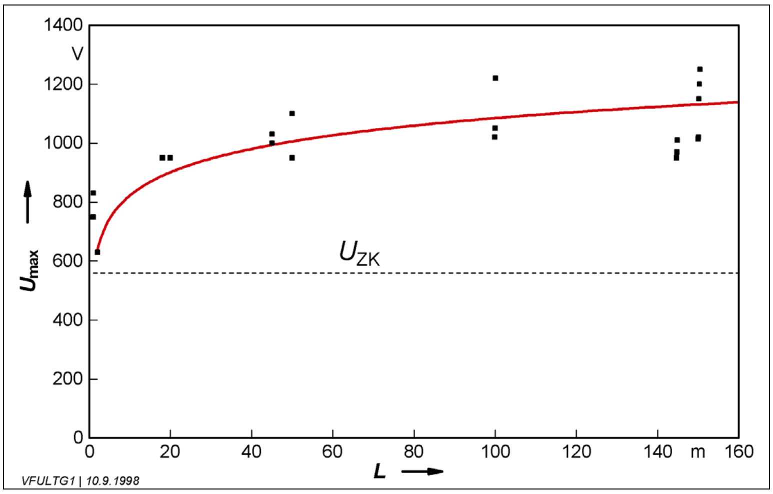


Fig. 5.2.3.2.5
Influence of the line length L on the voltage spike U_{max} in comparison to the intermediate circuit voltage U_{ZK} (in accordance with [3.6])

It would break the principles of converter feed if the voltage spikes were only countered by restricting the line length (Fig. 5.2.3.2.6). The correct solution from a technical point of view is to use *output filters* on the inverter.

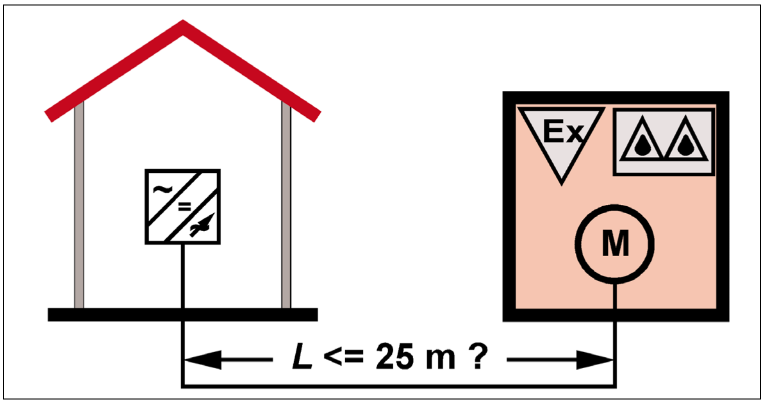


Fig. 5.2.3.2.6
One of the major advantages provided by the principle of inverter-fed drives would be lost by restricting the line length.

The user would be well advised to pick an inverter with an ***output filter*** in that the critical values are damped to such an extent that there is no risk to the winding insulation. The following values were measured at the output of a pulse-width modulation (PWM) inverter:

- without output filter $\hat{U} \approx 800$ V,
- with output filter $\hat{U} \approx 265$ V.

The actual expenditure on the output filter brings is richly compensated:

- increased security against premature winding damage,
- reduced noise emissions,
- better underlying conditions for the observance of EMC codes of practice, even without shielded motor cables.

5.2.4 Single-phasing

If one line conductor (phase) should fail, a three-phase motor (which requires three voltages differing in phase by one-third of a cycle to form a rotating field) continues to run on two phases. Where a malfunction of this type occurs, the motor is said to be running in two-phase mode and thus operates like a single-phase motor.
If the winding is configured for delta connection, “one phase” (phase winding) will overheat, whereas “two phases” are endangered with star connection.
These points show how interchangeable the terms are in common usage.
The reason: The term“ phase” ***should only be used for a transitory condition*** and ***not for the line conductors*** and the phase windings.
The following terms are adopted in this section:

Phase is the instantaneous wave condition of a periodic wave process.
Note: The conductors or devices assigned to the individual conducting paths of a polyphase system are also figuratively termed “phases” in the 1966 edition of DIN 40108. This use of the word “phase” to designate objects which is still common in technical circles is no longer recommended.
(Cf. DIN 40108, subclause 2.1 and DIN 1311 Part 1, subclause 3.4).

Line conductors are conductors which connect the current supplies and current consuming apparatus but do not originate at the neutral point or star point.
(Cf. DIN VDE 0100, Part 200, subclause 3.1 and DIN 40108, subclause 4.1.1)

A ***winding*** is the conducting path in polyphase systems along which the current of one phase (in the sense of “wave condition”) flows.
(Cf. DIN 40108, subclause 4.2)

Two-conductor operation is the faulty operation of a polyphase machine following the failure of an outer conductor.
This fault situation is also termed ***single-phasing***.

5.2.4.1 Causes of single-phasing

Wherever three-phase cage motors are used, there is the constant tendency for one of the three outer conductors to fail. This is usually caused by ***one*** fuse blowing due to a starting current inrush, but is sometimes caused by poor contact in the conductor routing or a wire breakage.
It is well known that, even in the event of single-phasing, a three-phase asynchronous motor retains virtually all its speed – albeit with reduced pull-out power– and continues to operate in the direction of rotation initiated by a motive impulse or prevailing prior to the malfunction.

5.2.4.2 Effect on current consumption and winding heating

The current in the two live line conductors increases by a factor of 1.2 to 2 over fault-free operation (Fig. 5.2.4.2). The magnitude of the increase is independent of

- size and design of the motor,
- utilisation (generally lower than the nominal torque as the pull-out torque is considerably reduced with single-phasing).

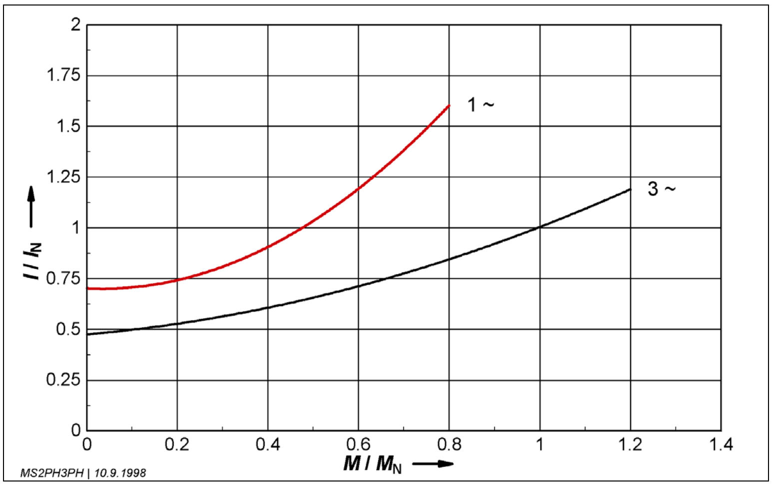


Fig. 5.2.4.2
Relative current in the supply line I/I_N under varying load M/M_N, in relation to the rated value under fault-free operation
3 ~ for three-phase operation (3 conductors)
1 ~ for single-phase operation (2 conductors)

In contrast to fault-free operation, the current in the two remaining outer conductors is not a measure of motor heating:

- In delta connection, the current distribution deviates from the normal ratio:
  fault-free operation: $1 : 1/\sqrt{3} = 1 : 0.58$,
  faulty operation: $1 : 2/3 = 1 : 0.67$.
- The contra-rotating (inverse) field causes additional losses in the rotor such that the temperature of the rotor may rise to double the rated value or more, particularly in the case of large motors with marked eddy current effect.
  The rotor temperatures heat the stator winding accordingly, particularly on closed surface-cooled machines (e.g. cooling type IC 411).
- The fact that stator winding parts are either not heated directly (one phase winding carries no current in the case of star connection) or carry only a reduced current (two phase windingd are connected in series in the case of delta connection) serves to lessen this effect.

It is not therefore possible to make a general statement on winding temperatures in single-phasing. Star winding connections would not be endangered if the overcurrent relay could prevent a current increase above the setpoint.

5.2.4.3 Effects on the current in the phase windings

Effects of the current distribution in the three phase windings of the motor and on the effectiveness of the normal motor protection relay for the two common configurations of the three-phase stator winding.

Star connection

With the windings in star connections, the relays in the mains supply line are arranged in series with the associated phase windings and so directly monitor the current to which the stator heating is proportional (Fig. 5.2.4.3.1). Although this current may at worst be up to 32 % greater than the rated current, there is generally no great risk to the winding since one phase winding (i.e. a third of the space occupied by windings) is not carrying any current and can compensate by absorbing a considerable amount of heat.

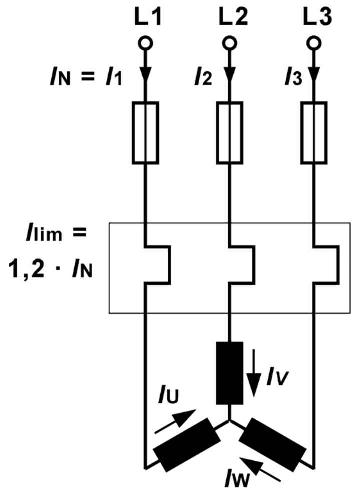
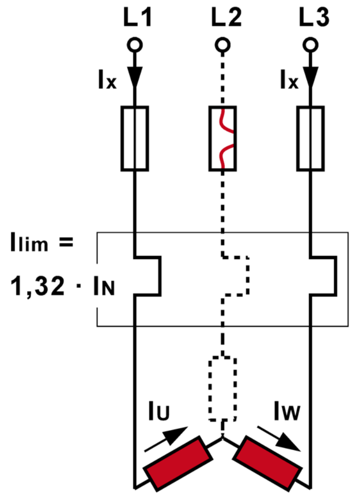
Three-wire operation fault-free	Single-phasing faulty
	
$I_{strg} = I_U = I_V = I_W = I_N$	$I_X = I_U = I_W \leq 1{,}32 \cdot I_N$ $I_V = 0$

Fig. 5.2.4.3.1 Current consumption for three-phase and single-phase operation in star connection

Delta connection

If one mains supply line fails in delta connection, one phase winding remains at full voltage while each of the two other phase windings receive only half the rated voltage. Therefore, the current distribution in the two branches is in the ratio 2 : 1 or 2/3 I_N : 1/3 I_N.
Even if the motor protection relay set at I_N does not permit more than this designated value to flow continuously in the endangered phase winding, a continuous current of 2/3 I_N = 0.67 I_N may have to be reckoned with, even though this phase winding is only capable of withstanding $1/\sqrt{3}\ I_N = 0.58\ I_N$ continuously.
In fact, an operating current of up to 1.32 I_N may flow in disrupted operation, i.e. up to 1.32 · 0.67 I_N = 0.88 I_N may flow in the endangered phase winding without the relay responding.
The phase winding is thus loaded with 0.88/0.58 = 1.5 times the permissible phase current. This represents a considerable danger, even if good heat exchange is present, in that the two other phases are loaded to only 75% of their rated value (Fig. 5.2.4.3.2).
Winding temperatures of up to 140 % of rated values have been measured where the outer line current corresponds to the rated current.
However, much higher currents may occur within the permissible standardized operating tolerances of the relays where special phase failure sensitivity is not used.

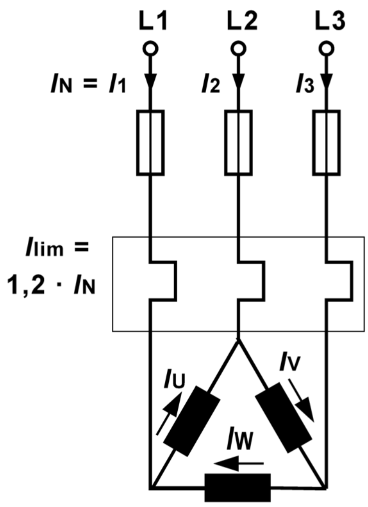
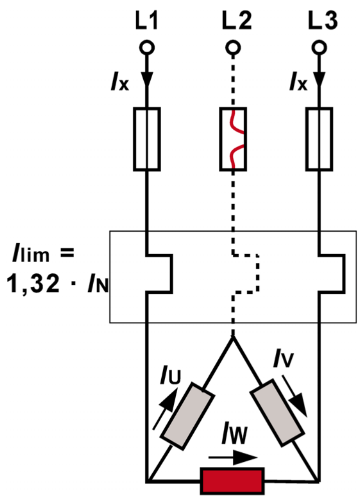
<table>
<tr><td>Three-wire operation
fault-free</td><td>Single-phasing
faulty</td></tr>
<tr><td>
</td><td>
</td></tr>
<tr><td>$I_{\text{strg}} = I_U = I_V = I_W = \frac{1}{\sqrt{3}} \cdot I_N = 0{,}58 \cdot I_N$</td><td>$I_U = I_V = \frac{1}{3} \cdot I_X$
$I_W = \frac{2}{3} \cdot I_X \leq 0{,}88 \cdot I_N \approx 1{,}5 \cdot I_{\text{strg}}$</td></tr>
</table>

Fig. 5.2.4.3.2 Current consumption for three-phase and single-phase operation in delta connection

5.2.4.4 Typical damage patterns on three-phase stator windings

The current ratios discussed in the previous section cause typical damage patterns which enable a precise diagnosis of the cause of damage (Figures 5.2.4.4.1 and 5.2.4.4.2).
If the user is advised accordingly, the weak points in the mains supply can be rectified and a repetition of the winding damage avoided.

Star connection

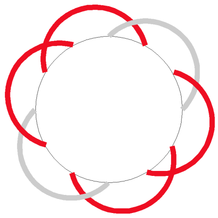
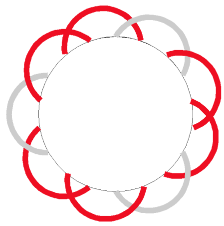
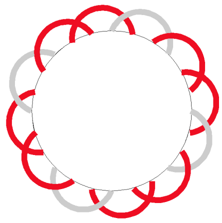
Number of poles	4	6	8
Damage pattern			

Fig. 5.2.4.4.1 Endangered coils (red) on the end winding of 4, 6, or 8-pole three-phase stator windings for single-phasing in star connection

Delta connection

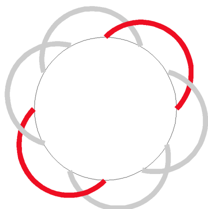
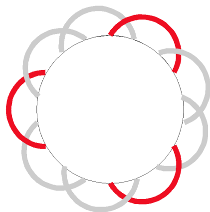
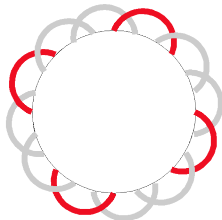
Number of poles	4	6	8
Damage pattern			

Fig. 5.2.4.4.2 Endangered coils (red) on the end winding of 4, 6, or 8-pole three-phase stator windings for single-phasing in delta connection

Special connections

The damage patterns above apply to the conventional connection and arrangement of the part-coils of a phase winding.
Special connections (e.g. a Dahlander pole-changing connection) and special windings (e.g. double-layer windings) produce different damage patterns. However, an expert can easily relate these to the patterns shown.

5.2.4.5 Response values of bimetal cut-outs

Test currents for overload relays and their tolerances are specified in EN 60947-4-1 / IEC 60947-4-1 (Table 5.2.4.5).

Table 5.2.4.5 Test currents for overload relays

Overload relay	Factor A	Factor B
3-pole loading	1.05	1.2
2-pole loading, not phase failure sensitive	1.05	1.32
2-pole loading, phase failure sensitive	1.0	1.15

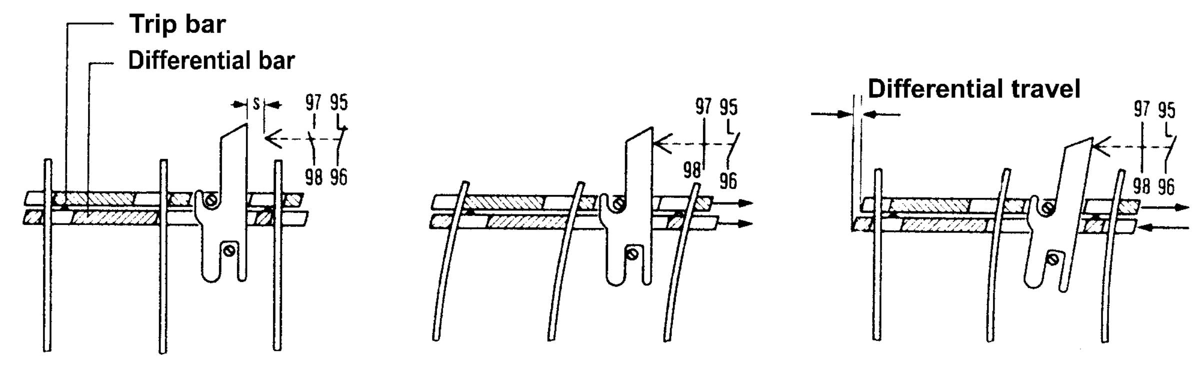
Tripping characteristics of 3-pole overload relays, temperature-compensated, at 20 °C (extract from EN 60947-4-1 / IEC 60947-4-1, tables 3 and 4):

A: Test current as a multiple of the setting current at which the relay must not trip within 2 hours of starting from cold,

B: Test current as a multiple of the setting current at which the relay must trip within less than 2 hours after Test A.

5.2.4.6 Phase failure sensitivity of motor protection relays

The danger posed to three-phase stator windings described (particularly in delta connection) and the relatively high rate of failure led to the development of “phase monitors” or “unbalance relays” as early as the 20s and 30s. These must usually be installed in addition to the overcurrent relay. ***Phase failure protection*** has only been more widely used since the introduction of “phase failure sensitivity” in the form of a relatively simple and cheap auxiliary component to the bimetal cut-out in the 60s. Extensive discussion at the time of the introduction of supplementary regulations on the protection of type “e” explosion-proof motors has contributed to the widespread use of this form of protection.
The Z motor protection relay manufactured by MOELLER is shown below (Fig. 5.2.4.6) as representative of the various solutions available on the market. When the bimetal strips in the main current section of the relay deflect as a result of a motor overload on three phases, all three act on a trip bar and a differential bar (Fig. 5.2.4.6). A common trip lever switches over the auxiliary contact when the limit values are reached. The trip and differential bar lie against the bimetal strips with uniform pressure. If, for example, in the event of phase loss one bimetal strip does not deflect or recover as strongly as the other two, then the trip and differential bars will cover different distances. A step-up mechanism utilizes this differential movement to create an additianal tripping movement, and thus accelerates the tripping action. This applies irrespeative af which phase actually fails.



Fault-free normal operation	Overload in all three lines	Failure of one line; single-phasing

Fig. 5.2.4.6 Principle of the phase failure sensitivity of a bimetal relay (Z motor protection relay manufactured by MOELLER)

5.2.4.7 Phase failure protection for type “e” explosion-proof motors

When the new version of installation regulations DIN VDE 0165 was issued in 1976, discussions on the subject were drawn-out and sometimes highly theoretical. The standard EN 60079-14 / IEC 60079-14 currently in force in 7 simply specifies:
"Precautions shall be taken to prevent the operation of a three-phase motor on the loss of a phase."
The following rather lengthly wording has been dicussed for an amendment of 11.2.1 of these standards:
"The properties of delta wound machines in case of loss of one phase should be specifically addressed. Unlike star wound machines, the loss af one phase may not be detected, particularly if it occurs during operation. The effect will be current imbalance in the lines feeding the machine and increased heating of the motor. A delta wound motor with a low torque load during start-up might also be able to start under this winding failure condition and therefore the fault may exist unknown for long periods. Therefore, for delta wound machines, phase imbalance protection shall be provided which will detect machine imbalbances before they can give rise to excessive heating effects."

5.2.4.8 Summary of phase failure sensitivity

The danger of damage to a winding resulting from single-phasing following a mains fault can be significantly reduced by the use of bimetal relays with phase failure sensitivity. These additional protective devices are particularly recommended for ***medium-size and large motors in delta connection*** as they can further reduce the already low rate of winding damage on standard three-phase motors.
These devices are mandatory on explosion-proof type of protection “e” motors.

5.3 Duty types

With the exception of drives for special applications (e.g. hoists), standard motors are always designed for continuous running duty. Where drives are subject to frequent switching, it may be necessary to choose a special design in a larger frame size. Conversely, it may be possible to select a much smaller model for truly short-time duty. ***It is therefore necessary to advise the manufacturer of any duty type which differs from continuous running duty. Doing so may also result in cost savings***.
The increasing automation of manufacturing processes has brought about a situation where electric drives are subjected to cyclical operation or used for positioning, that is to say in switched and braking duty.It has therefore become necessary to expand on the long-established terms such as “continuous running duty”, “intermittent periodic duty” or “short-time duty” to define the thermal rating of a drive. The description of duty types in the internationally harmonized version of EN 60034-1 / EIC 60034-1 runs to 13 pages of A4. Unfortunately, the text is not always clear, despite its length. Extracts from it have been reproduced below as necessary to provide a general overview.The schematic diagrams and abbreviations for variables have been changed from those used in the standard to improve intelligibility [2.4].
Recommendations and measures on overload protection differ according to the duty type.

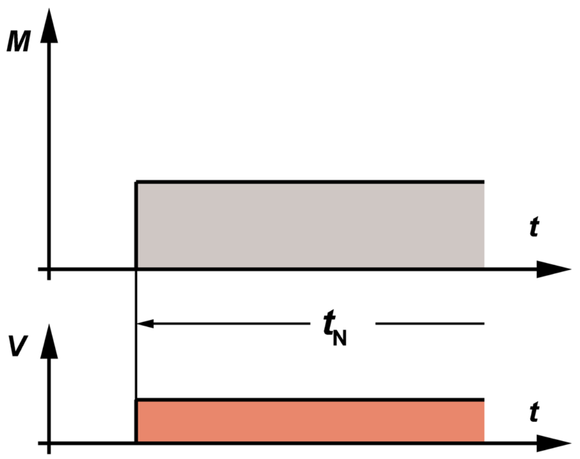
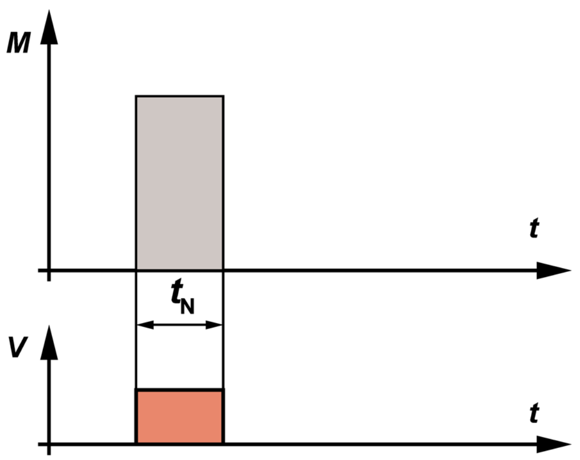
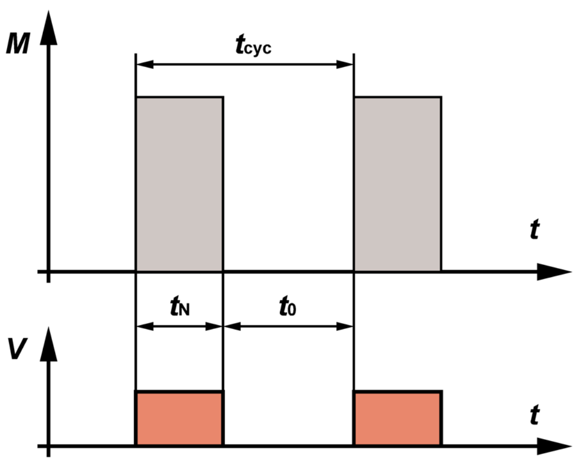
5.3.1 Classification

Table 5.3.1 shows the classification of duty types of electrical machines in accordance with [1.6]. The abbreviations used have the following meanings:

M	Load
V	Electrical losses
t	Time
t_{cyc}	Period of one cycle
t_a	Starting time
t_N	Operating time at constant load
t_{Br}	Time with electrical braking
t_0	Time at rest and de-energised

Cyclic duration factor = $(t_a+t_N+t_{Br}) / t_{cyc}$

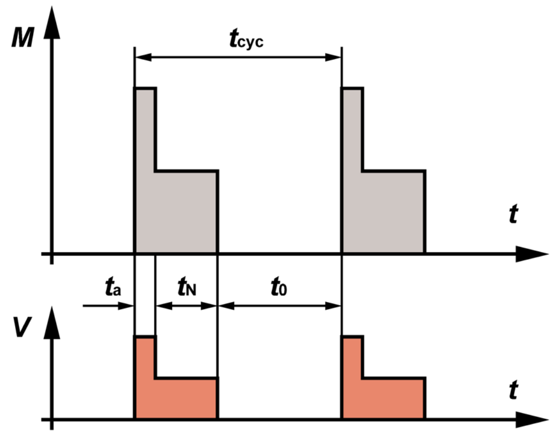
Table 5.3.1 Duty types of electrical machinery

Designation previously common Simplified categorization	**Abbreviations and definitions in accordance with the standard**
Continuous running duty	**S1**
	**Continuous running duty** Operation at constant load of sufficient duration for thermal equilibrium to be reached. The corresponding designation is S1.
Short-time duty	**S2**
	**Short-time duty** Operation at constant load during a given time less than that required to reach thermal equilibrium, followed by a rest and de-energized period of sufficient duration to re-establish machine temperatures within 2 K of the coolant. The corresponding designation is S2, supplemented by specification of the operating time. For example: S2 — 60 min
Intermittent periodic duty	**S3**
	**Intermittent periodic duty** A sequence of identical duty cycles, each including a period of operation at constant load and a rest and de-energized period. In this duty, the cycle is such that the starting current does not significantly affect the temperature rise. The designation is S3, supplemented by the cyclic duration factor. For example: S3 — 25%

Intermittent switched duty

S4

Intermittent periodic duty with starting



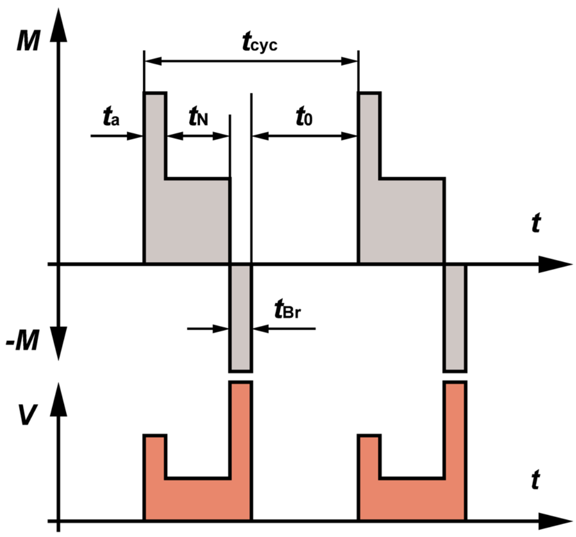
A sequence of identical duty cycles, each cycle including a significant period of starting, a period of operation at constant load and a rest and de-energized period.

The corresponding designation is S4, supplemented by the cyclic duration factor, the mass moment of inertia of the motor (J_M) and the mass moment of inertia of the loading machine, (J_{ext}), both in relation to the motor shaft.

For example: S4 — 25% J_M = 0.15 kgm^2

S5

Intermittent periodic duty with electric braking



A sequence of identical duty cycles, each cycle consisting of a period of starting, a period of operation at constant load, a period of rapid electric braking and a rest and de-energized period.

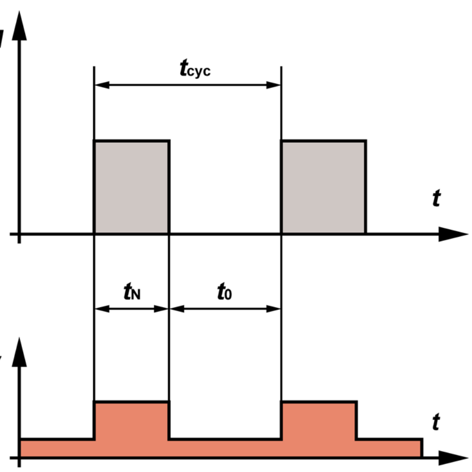
The corresponding designation is S5, supplemented by the cyclic duration factor, the mass moment of inertia of the motor (J_M) and the mass moment of inertia of the loading machine, (J_{ext}), both in relation to the motor shaft.

For example: S5 — 25% J_M = 0.15 kgm^2

J_{ext} = 0.7 kgm^2

S6

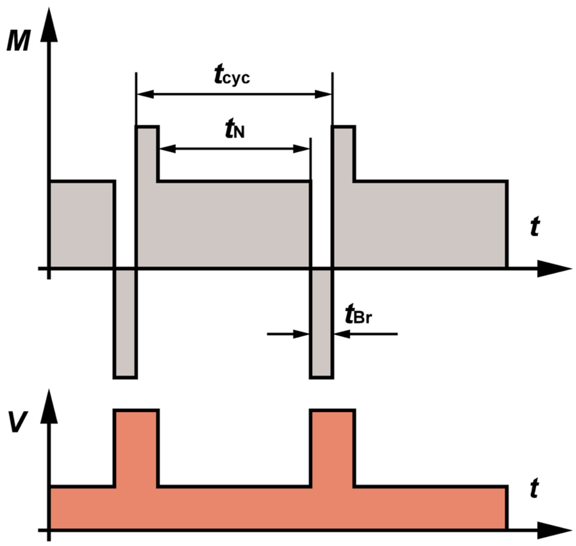
Continuous-operation periodic duty



A sequence of identical duty cycles, each cycle consisting of a period of operation at constant load and a period of operation at no-load. There is no rest and de-energized period.

The corresponding designation is S6, supplemented by the cyclic duration factor.

For example: S6 — 40%

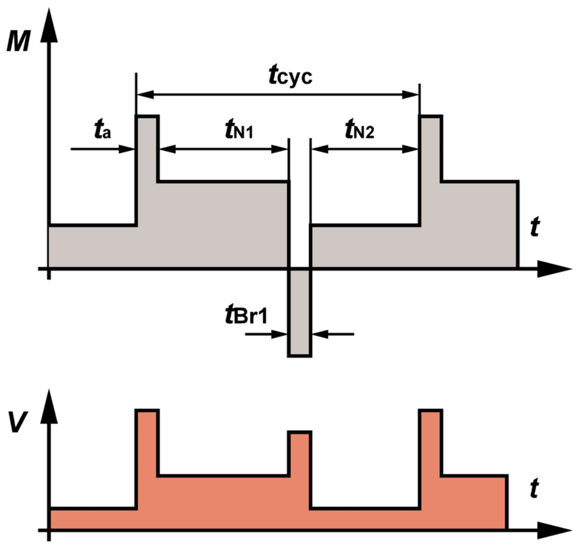
<table>
<tr><td>DSB — Continuous running switched operation</td><td>S7</td></tr>
<tr><td>
</td><td>

Continuous-operation periodic duty with electric braking

A sequence of identical duty cycles, each cycle consisting of a period of starting, a period of operation at constant load and a period of electric braking. There is no rest and de-energized period.

The corresponding designation is S7, supplemented by the mass moment of inertia of the motor (J_M) and the mass moment of inertia of the loading machine, (J_{ext}), both in relation to the motor shaft.

For example: S7 — J_M = 0.4 kgm² J_{ext} = 7.5 kgm²

Cyclic duration factor = 1
</td></tr>
<tr><td></td><td>S8</td></tr>
<tr><td>
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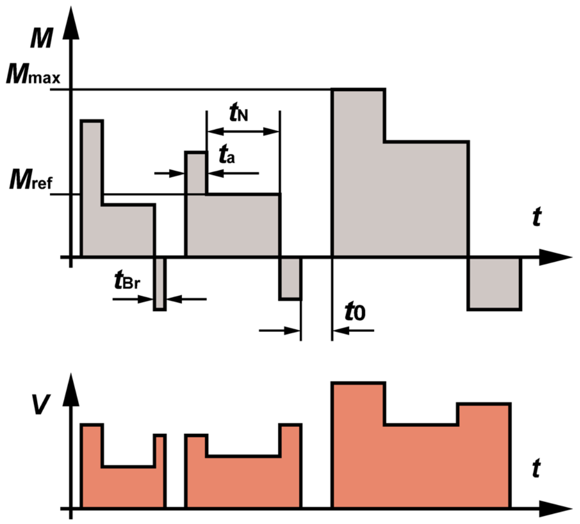
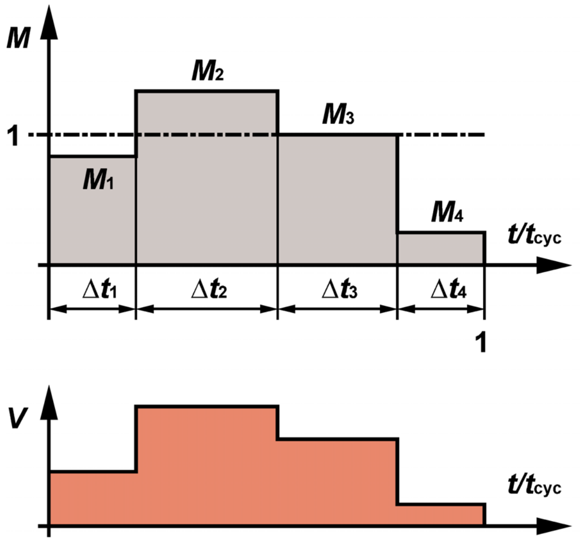
Continuous-operation periodic duty with related load/speed variations

A sequence of identical duty cycles, each cycle consisting of a period of operation at constant load corresponding to a predetermined speed of rotation, followed by one or more periods of operation at other constant loads corresponding to different speeds of rotation (carried out for example by means of a change of the number of poles in the case of induction motors). There is no rest and de-energized period.

The corresponding designation is S8, supplemented by the mass moment of inertia of the motor (J_M) and the mass moment of inertia of the loading machine (J_{ext}), both in relation to the motor shaft and the speed of rotation and the load, speed of rotation and cyclic duration factor for each speed of rotation in question.

For example: S8 — J_M = 0.5 kgm² J_{ext} = 6 kgm²

16 kW 740 r/min 30 % / 40 kW 1460 r/min 30 %
</td></tr>
</table>

	S9
	**Duty with non-periodic load and speed variations** A duty in which load and speed generally vary non-periodically within the permissible operating range. This duty includes frequently applied overloads that may greatly exceed the full loads. The corresponding designation is S9. For this duty type, a constant load appropriately selected and based on duty type S1 is taken as the reference value (M_{ref}) for the overloading.
	S10
	**Duty with discrete constant loads** A duty consisting of not more than four discrete values of load (or equivalent loading), each value being maintained for sufficient time to allow the machine to reach thermal equilibrium. The minimum load within a duty cycle may have the value zero (no-load or rest and de-energized)

The corresponding designation is S10, supplemented by the related variable $p/\Delta t$ for the particular load and its application time, as well as the related variable TL for the relative service life expectancy of the insulation system. The reference value for the thermal service life expectancy is the thermal service life expectancy as measured for continuous running duty and taking into account the permissible temperature rise limit values in accordance with duty type S1. The load must be designated with the letter r for time at rest and de-energized.

For example:
S10 $p/\Delta t$ = 1.1/0.4, 1/0.3, 0.9/0.2, r/0.1, TL = 0.6

The numerical value of TL should be rounded to 0.05.

For this duty type, a constant load appropriately selected and based on duty type S1 should be taken as the reference value for the specific loading.

Note:
The discrete values at load will usually be equivalent to continuous running duty based on integration over a period of time. It is not necessary that each load cycle be exactly the same, only that each load within a cycle be maintained for sufficient time for thermal equilibrium to be reached, and that each load cycle be capable of being integrated to give the same thermal life expectancy.

5.3.2 Continuous running duty S1

The following function applies to the temperature rise of an electrical machine under simplified assumptions and constant conditions (load, ventilation, ambient temperature):

$$\vartheta = \Theta_{max}\left(1 - e^{-\frac{t}{\tau}}\right)$$

$\Theta_{max} \leq \Theta_{lim}$ applies to a motor designed for continuous running duty S1.

ϑ	Temperature rise in K
Θ_{max}	Maximum temperature rise attained at equilibrium between heat input and cooling
Θ_{lim}	Limit temperature for the thermal classification
t	Load time
τ	Time constant (characteristic value for the size and cooling of a machine)
e	Natural logarithm (approximately 2.72)

The ***equilibrium temperature*** Θ_{max} of the machine must not exceed the maximum permissible temperature rise Θ_{lim} specified for its thermal classification in [1.6]. The ***time constant*** τ is long if the machine is large and/or relatively poorly ventilated. It is relatively short for small and/or well ventilated machines. Fig. 5.3.2.1 uses a schematic diagram to show the effect of the time constant on the temperature rise curve.

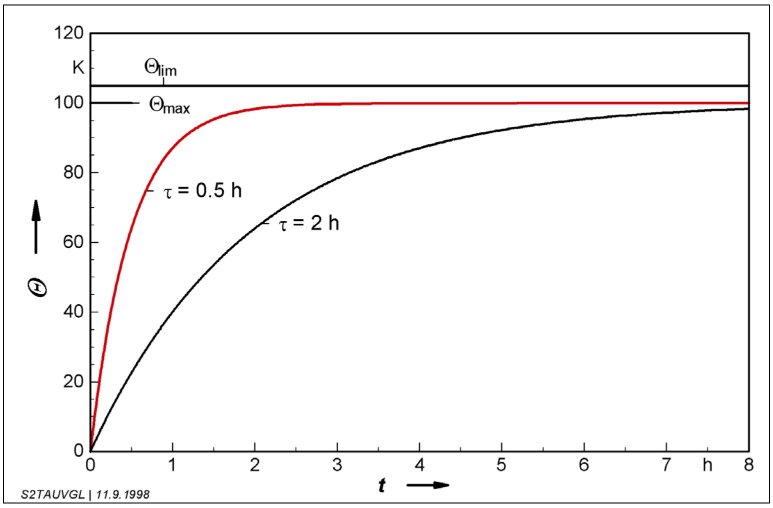


Fig 5.3.2.1
Schematic diagram of the temperature rise
τ = 0.5 Relatively small and/or well ventilated machines
τ = 2 Relatively large and/or poorly ventilated machines

A higher load (heat loss) would result in a higher end temperature rise Θ_{max} in continuous running duty S1; the increase in heating must therefore be kept within the permissible limits by restricting the time. Fig. 5.3.2.2 uses a schematic diagram to show that the more the machine is overloaded, the shorter the permissible operating hours. The bimetal relay performs the function of a current-dependent timer. However, due to its low mass in comparison to the motor, the metal relay trips earlier than the motor would permit. Using the simplified principle of the example given in Fig. 5.3.2.2 which states that approximately 1.5 times the current flows for 1.5 times the output, a motor protection relay would trigger after approximately 2 minutes from a cold start even though the motor is not in danger until more than an hour has passed under the same conditions.
The following formula (the so-called linear-quadratic conversion) often adopted in practice can be used for the temperature rise of the winding in the range of approximately (0.75 to 1.25)P_N:

$$\vartheta_x = \frac{\frac{P_x}{P_N}\cdot\vartheta_N + \left(\frac{I_x}{I_N}\right)^2\cdot\vartheta_N}{2}$$

ϑ	Temperature rise
P	Output
I	Current consumption
Index N	at the rated point
Index x	at any load point (0.75 to 1.25)P_N

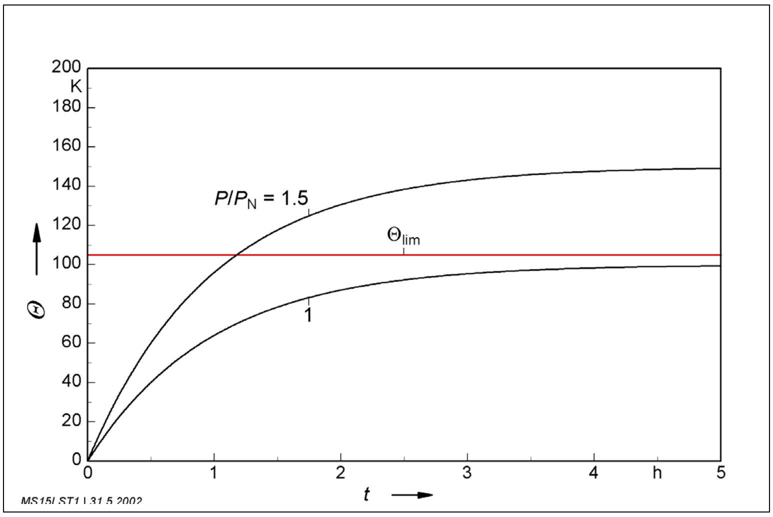


Fig. 5.3.2.2
Variation of the temperature increase
with overloading $P/P_N = 1.5$ compared to the
rated output $P/P_N = 1$

θ_{lim} Maximum temperature rise for temperature class F

5.3.3 Short-time duty S2

The high overload capacity of three-phase cage motors – depending, of course, on the model – as discussed in the previous section poses no risk under certain applications and can be used to cut costs by specifying “1.5P_N – 1h” on the motor's rating plate. The motor protection relay is set at the increased current and so ***does not trigger after one hour.*** The current cannot be used as a measurement of heating for duty types S2 and S3; current-dependent delayed thermal over-current relays are therefore only suitable as a protection against blocking caused by the rotor locking. The ***operating hours*** or the ***winding temperature*** must be monitored. The running time for S2 applications is often limited in any case: factory gates, shutters, hoists are examples of this type of application. The running time and duration of rest periods must otherwise be monitored. Thermal motor protection (TMS) by means of thermistors is another reliable method.
The definition of duty type S2 states that the load period must be followed by a rest and de-energized period of sufficient duration for the machine to cool to a temperature within 2 K of the coolant temperature of the coolant. The ***cooling time constant*** is considerably longer than the operating time (by a factor of 4, for instance) due to the lack of ventilation. This results in a relatively long cooling time (Fig. 5.3.3.1 and Table 5.3.3.2).

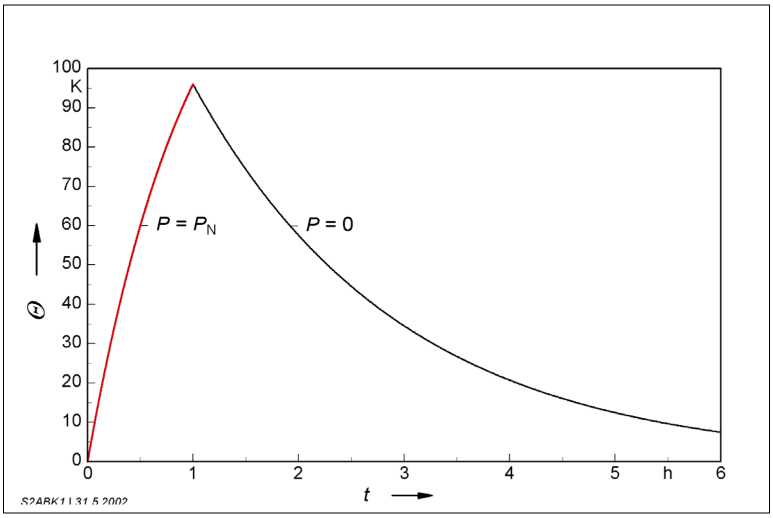


Fig. 5.3.3.1
Schematic diagram of heating (P=P_N) and cooling (P=0) of an S2 motor

Table 5.3.3.2 Typical cooling times after short-time duty S2

Motor shaft height (mm)	56 to 80	90 to 112	132 to 180	200 to 280
Cooling time (minutes)	80	160	240	360

5.3.4 Temperature curve for S3

Neither the end temperature under load nor the ambient temperature in the rest and cooling period is attained in a single cycle for duty type S3. The temperature curve approximates to a transient condition in which the temperature oscillates in a saw-tooth pattern between a maximum value ϑ_{S3max} and a minimum value ϑ_{S3min}. As specified in [1.6], subclause 15.5.3.7.2, the temperature cycle is considered equivalent (transient) if an imaginary line connecting the limit values has a gradient of less than 2 K/h (Fig. 5.3.4.1).
The temperature in the centre of the time section must not exceed the limit temperature of the particular temperature class (Fig. 5.3.4.2).

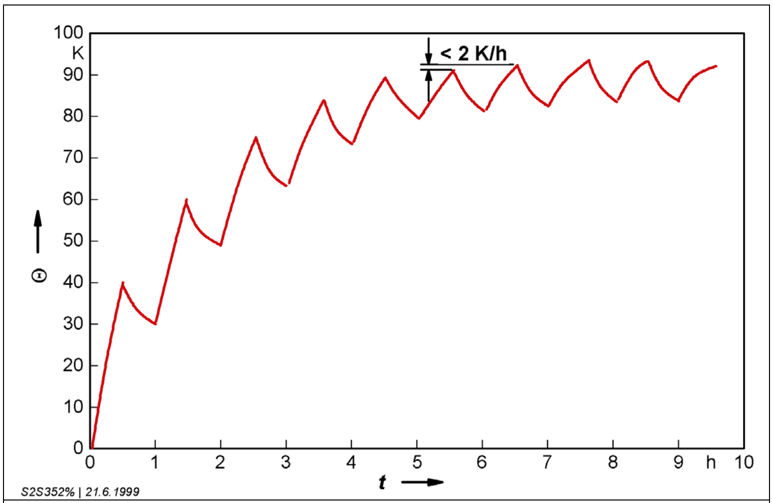


Bild 5.3.4.1
Schematic diagram of temperature ϑ for duty type S3 - 50 %

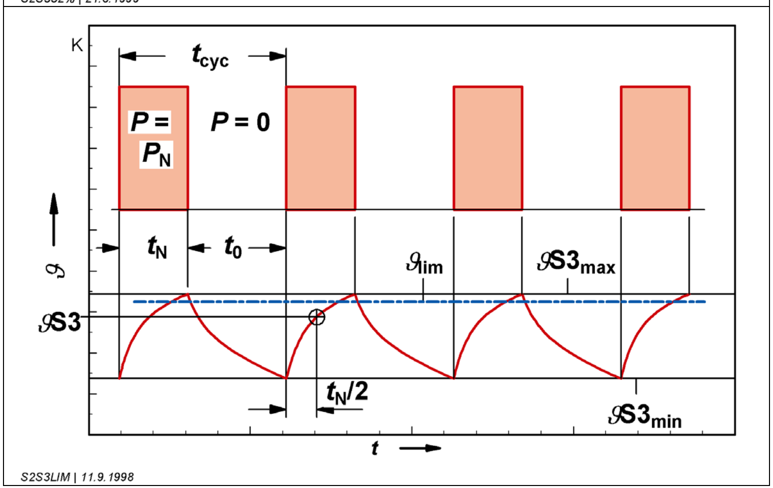


Fig. 5.3.4.2
Determination of the rated temperature rise ϑ_{S3} for duty type S3 - 40 % after half the time of a load interval t_N for a transient temperature curve between the limits ϑ_{S3min} and ϑ_{S3max}

The rated temperature rise must be below the maximum temperature rise ϑ_{lim} .

Similar considerations apply to the overload protection as for duty type S2. However, monitoring the time is too complicated in the case of S3 so TMS (thermal motor protection) provides the protection instead.

5.3.5 Intermittent periodic duty with starting S4

The total heating of the winding and cage rotor for this duty type is governed by the severity and number of start-up operations. Manufacturer-specific, but fundamentally similar, methods using the characteristic Z_0 obtained through experimentation for the ***permissible no-load switching frequency*** are common for the prediction of the permissible switching frequency [2.4], [2.8].
Current-dependent delayed thermal over-current relays are not suitable as a means of overload protection as they do not reflect the temperature of the winding. They would trigger far too early under the influence of a high switching frequency. Relay manufacturers' catalogues quote 25 to 60 c/h as the maximum permissible switching frequency. In isolated instances, this guide value can be significantly exceeded as shown in Figures 5.3.5.1 and 5.3.5.2 based on [2.10].

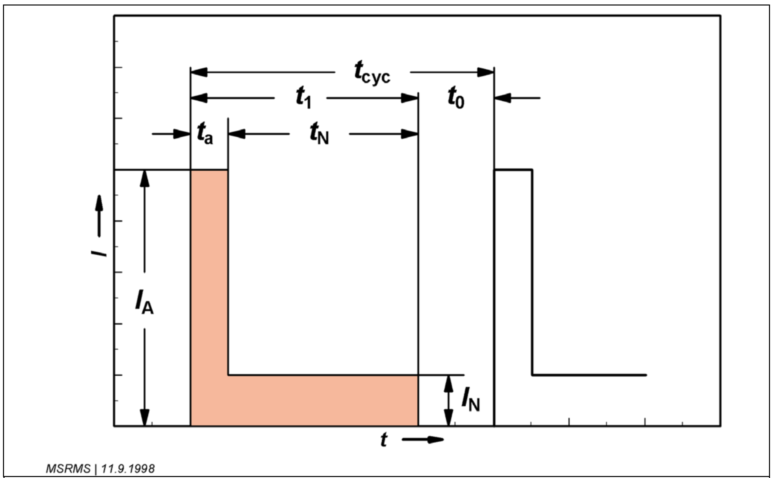


Fig. 5.3.5.1
Characteristic variable for intermittent switched periodic duty

t_{cyc} - Cycle time
t_1 - Total operating time
t_N - Running time at rated current I_N
t_a - Starting time at starting current IA
t_0 - At rest and de-energized

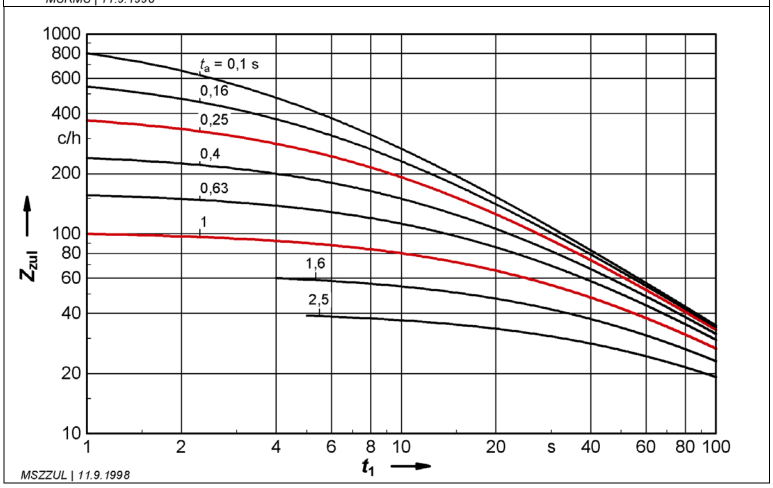


Fig. 5.3.5.2
Thermally permissible switching frequency Z_{zul} of bimetal relays
See for explanatory notes

These guide values simply enable the permissible switching frequency of the relay to be estimated. The use of thermal machine protection (TMS) in accordance with subclause 6.2 is recommended for duty type S4 in ***combination with a bimetal relay*** set sufficiently high that it does not trigger at the maximum switching operation.

5.3.6 Reversing the direction of rotation

To ***reverse*** a motor, the line conductors connected to the supply for clockwise rotation are changed over to anti-clockwise rotation without a break. The field, now rotating in the anti-clockwise sense, first of all brakes the clockwise rotating mass moment of inertia until it comes to rest and then accelerates it up to speed in the anticlockwise direction (Fig. 5.3.6.1).
By "plugging" the motor in this way, the surge causes approximately four times the lost energy which would occur if the motor were switched off from clockwise rotation, allowed to coast to rest and then switched on for acceleration in the anti-clockwise direction.

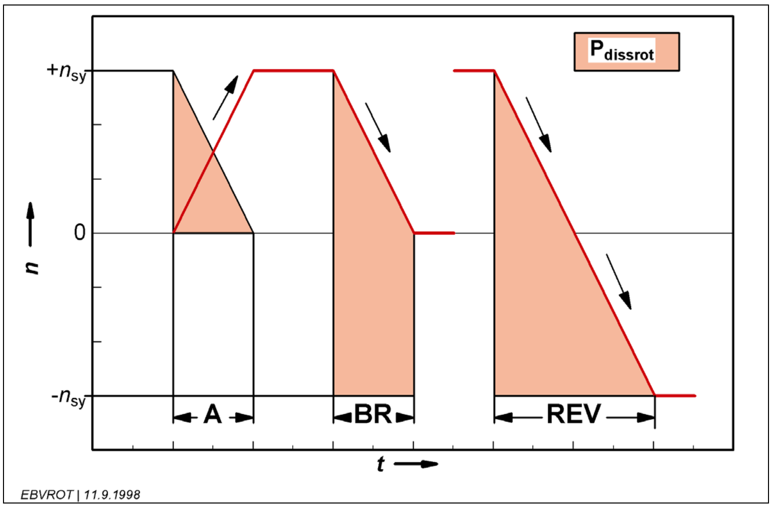


Fig. 5.3.6.1
Schematic diagram illustrating the following terms:
starting (A),
plugging (BR) and reversing operation (REV)
and
the respective rotor losses $P_{diss_{rot}}$

The actual factors specified in Table 5.3.6.1 for the thermal rating of a reversing operation are commonly used to enable the edda current effects to be taken into account.

Table 5.3.6.1 Factor for the thermal rating of reversing operations

Rated output of motor	P_N (kW)	≤ 1.5	≤ 7.5	≤ 22	≤ 50
Thermal rating of reversing operation : starting	K_R	3	2.8	2.6	2.4

5.3.7 Changing the speed

Pole-changing motors with two or more speeds should always be switched on via the lowest possible speed when starting. This will reduce the starting current and heat losses.

The rotor losses during pure flywheel starting are equal in theory to the energy imparted to the accelerated masses after run-up. Thus, after start-up, the total rotor loss will be given by

$$\boldsymbol{W_{rot}} = \frac{\boldsymbol{J \cdot \varpi^2}}{\boldsymbol{2}} = \frac{\boldsymbol{J \cdot n^2}}{\boldsymbol{182{,}5}}$$

The losses can be shown graphically as in Fig. 5.3.7.1. At the moment of switching on, the rotating field Φ almost instantaneously jumps to the synchronous speed of rotation n_{sy}, whereas the rotor is accelerated to this speed over time t_a. The difference between the rotating field speed n_{sy} and that of the rotor n_{rotor} is a measure of the power losses. The triangle over time t_a represents the lost energy V_{rotor} in the rotor.

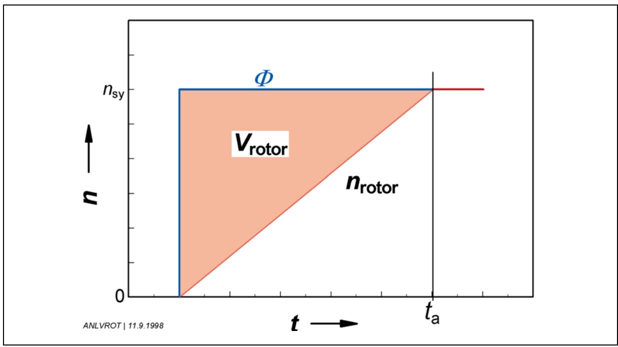


Fig. 5.3.7.1
Lost energy in the rotor V_{rotor} for direct-on-line starting with full rotating field speed n_{sy}

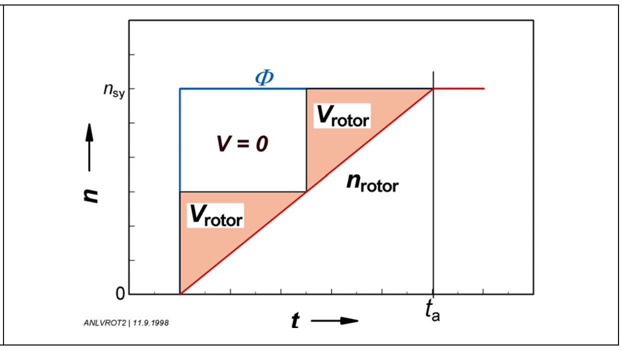
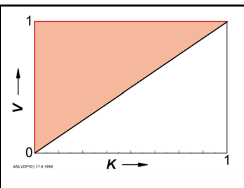
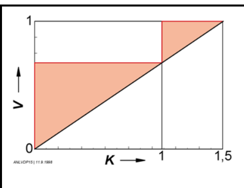
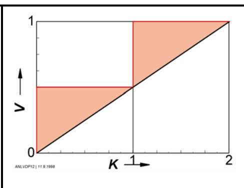
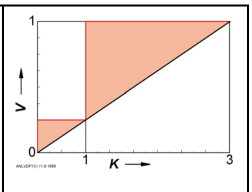
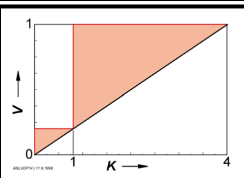
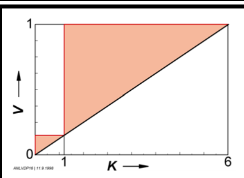
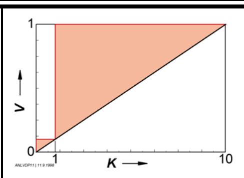


Fig. 5.3.7.2
Lost energy in the rotor V_{rotor} with stepped run-up by 1:2 pole-changing (e.g. 4/2 pole), the unshaded area V=0 being loss-free

With stepped run-up (e.g. by pole-changing with speed ratio of 1 : 2 as in Fig. 5.3.7.2), the lost energy is reduced to a half compared with direct-on-line switching (V_{rotor} = 0.5).

With other pole number ratios, the energy saving will be less (Table 5.3.7.3).

Table 5.3.7.1 Lost energy (red areas) and loss saving (light rectangles) with stepped starting by pole-changing with speed ratio K

Diagram				
Number of poles	e.g. 4	6/4	8/4, 4/2	6/2
Ratio K	1	1:1.5	1:2	1:3
Relative loss R	1	0.555	0.5	0.555
Diagram				
Number of poles	8/2	12/2	20/2	
Ratio K	1:4	1:6	1:10	
Relative loss R	0.625	0.72	0.82	

5.3.8 Electrodynamic braking

This term draws attention to three important properties of this method of braking:

- ☐ The process involves the braking effect of an induced conductor in the magnetic field, i.e. the process functions ***without physical contact or wear***.
- ☐ The braking effect is ***dynamic*** and therefore is operative only while the machine is rotating. There is no braking effect (*i.e.* ***no clamping brake***) while the machine is at rest.
- ☐ The motor winding is subjected to additional ***thermal loading*** by the braking.

Depending on the braking process, different parts of the torque/speed characteristic curve of a three-phase asynchronous motor come into play.

5.3.8.1 Hyper-synchronous regenerative braking

When a loaded hoist is descending, the motor will be driven at hyper-synchronous speed – although this is not perceptible to the operator – and will thus be delivering power back to the mains as an asynchronous generator.

The ***generative torque characteristic*** when working in this hyper-synchronous range will be almost a mirror image of the normal speed of rotation n_{sy}: However, the equivalent to **the *pull-out torque when generating*** will be significantly greater than the pull-out torque when motoring (Fig. 5.3.8.1). Although the shock load of changing from a higher to a lower speed can cause faults (see section 5.3.8.4), the steady lowering mode provides a safety factor with stepless since a load raised by a motor cannot "break through" the "braking generator" – even with a two-wire connection (that is to say, even if the pull-out torque were drastically reduced to 50 % of that of a three-wire connection), the braking torque would be sufficient to lower the load safely without undue rise in speed.

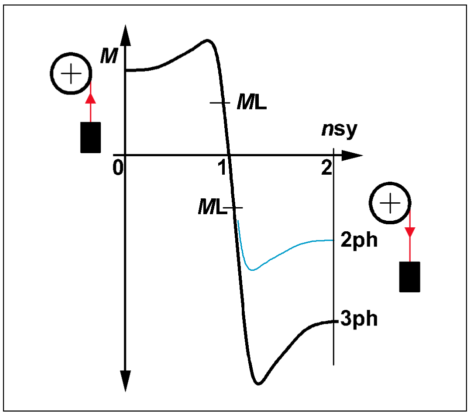


Fig. 5.3.8.1
Lowering a load (M_L) in hyper-synchronous regenerative mode with three-wire connection (3ph) and two-wire connection (single-phasing operating 2ph)

5.3.8.2 Plugging (reverse field braking)

In ***plugging operation*** (***reverse field braking*)**, the mass moments of inertia of the drive are decelerated to a stop in the same way as in the first part of a reversing operation. As the speed change passes through zero, the plugging contactor is opened by a ***braking monitor (zero speed switch)*** to prevent the driving motor from re-starting in the reverse direction (Fig. 5.3.8.2.1).

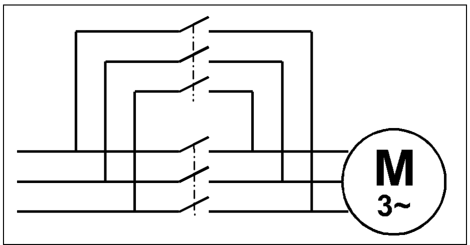


Fig. 5.3.8.2.1
Basic circuit diagram for plugging

Although plugging would appear to be simple both in its effect and in its circuitry, in practice there are two important limitations:

- ☐ The mechanical shock load can be unacceptably high, particularly where the transmission components have some lost motion or backlash, such as chain drives and claw couplings for the conveyance of goods and equipment.
- ☐ The difficulty of opening the plugging contactor at exactly zero speed becomes greater as the braking period is shortened (Fig. 5.3.8.2.2). Timers cannot register the effect of different loads and mass moments of inertia and speed of rotation detectors will involve increased costs.

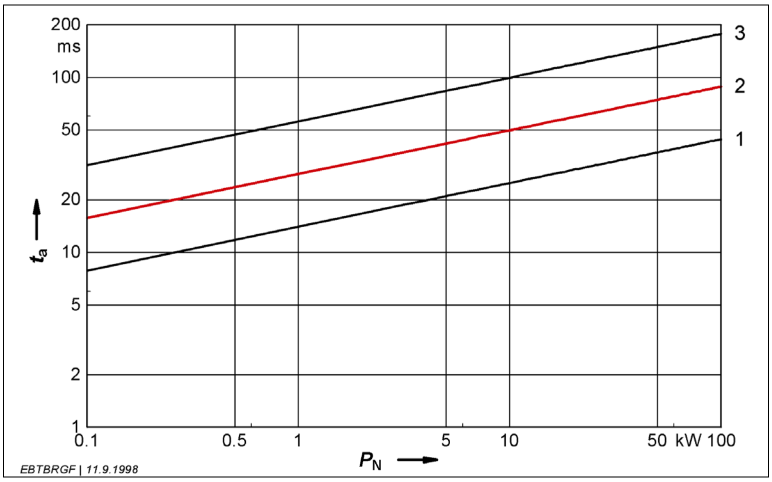


Fig. 5.3.8.2.2
Guide values for the plugging times for 4-pole three-phase cage motors, showing the effect of the factor of inertia *FI* (relative external inertia) and M_L (load torque)

1 *FI*=1, M_L=1 (Load torque = friction assists braking)

2 *FI*=1, M_L=0

3 *FI*=2, M_L=0

There are, however, areas of application where plugging is very popular. It is frequently used, for instance, for roller table drives since this method requires ***no additional equipment costs***. Because the friction between the rollers and the workpiece forms a limit to the maximum deceleration which can be transmitted, the braking periods usually lie within a range which can be *visually monitored*. The operator can therefore manually "counter" the plugging contactor by switching it off so that the braking process does not go beyond zero speed.
It is relatively unusual to find systems which stop the plugging process ***automatically*** in roller table applications since, under these arduous types of duty, such refinements may cause other problems.

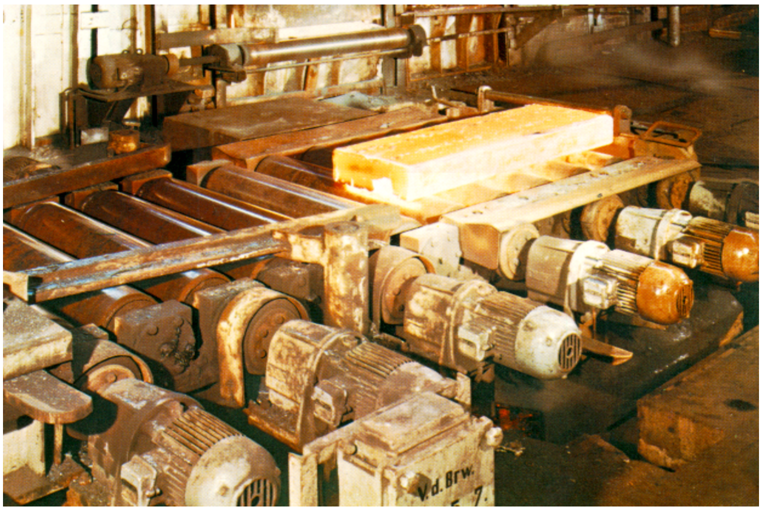


Fig. 5.3.8.2.3
Example of a roller table application suitable for plugging

The actual factors specified in Table 5.3.8.2.4 for the thermal rating of plugging are commonly used to enable the eddy current effects to be taken into account.

Table 5.3.8.2.4 Factor for the thermal rating of plugging operations

Rated output of motor	P_N (kW)	≤ 1.5	≤ 7.5	≤ 22	≤ 50
Thermal rating of plugging : starting	K_G	2	1.8	1.6	1.4

5.3.8.3 D.C. injection braking

If the three-phase winding of the stator is fed with direct current, a *stationary magnetic field* Φ will be set up in the stator bore causing a voltage to be induced in the bars of the cage rotor as long as the rotor is in motion (Fig. 5.3.8.3.1).

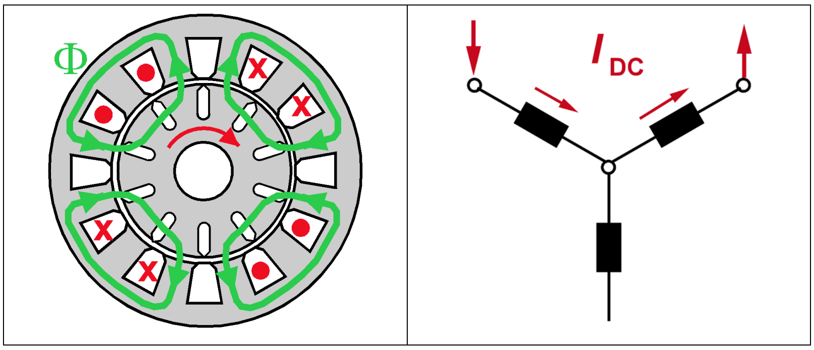


Fig. 5.3.8.3.1
Field developed by D.C.supply to a 4-pole three-phase stator winding in star connection

Since the electrical resistance of the rotor cage is very low, even small induced voltages can create a high rotor current.This current will produce a strong braking effect on the bars and hence on the rotor. As the speed falls, the frequency of the induced voltage falls and with it the inductive impedance. The ohmic resistance of the rotor gradually becomes dominant and so increases the braking effect as the speed comes down. The braking torque generated falls away steeply just before standstill and finally ceases when there is no further movement (Fig. 5.3.8.3.2).
Direct current injection braking ***is therefore not suitable for actually holding a load at rest***. On the other hand, ***the initially gentle but increasingly powerful effect*** of this method of braking makes it virtually ideal for almost any retardation process. This braking method is discussed in full in [2.8].

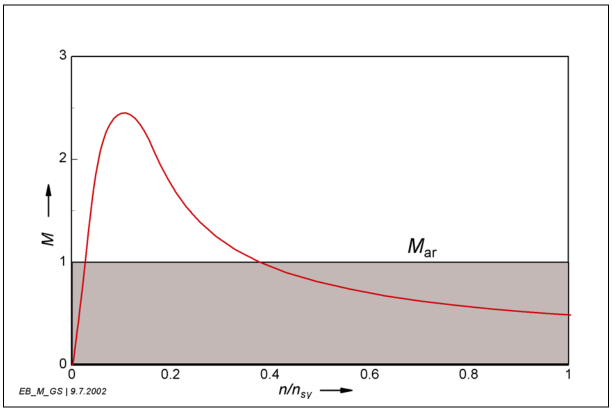


Fig. 5.3.8.3.2
Effectiveness of D.C. injection braking during retardation of speed from $n \rightarrow 0$
M Instantaneous braking torque
M_{ar} Average value of the braking torque

5.3.8.4 Pole-changing

Pole-changing cage motors with speed ratios of 1 : 2, 1 : 3, 1 : 4, 1 : 6 or 1 : 10 are frequently used for inching. ***A single*** winding in ***Dahlander connection*** is all that is required for a speed ratio of 1 : 2. All other speed ratios need ***two separate stator windings***, which of course involves lengthier manufacturing processes and consequently higher costs. Nevertheless, they are in many cases less expensive than motors with stepless speed control, such as D.C. or inverter-fed motors.
Regenerative braking will always occurs if the instantaneous speed *n* of the rotor is greater than the synchronous speed of the stator's rotating field. This occurs, for example, where pole-changing three-phase motors are switched from a lower number of poles to a higher number of poles. This causes a retardation torque due to regeneration and the effect will depend on the number of poles or speed ratio and on the type of motor.
Figure 5.3.8.4 shows the shape of the speed/torque characteristic curve in the motoring and regenerative ranges. The regenerative braking torques are considerably greater than the motoring torques.
Short noises may be heard in regenerative braking; these are above the normal operating sound of the three-phase machine.

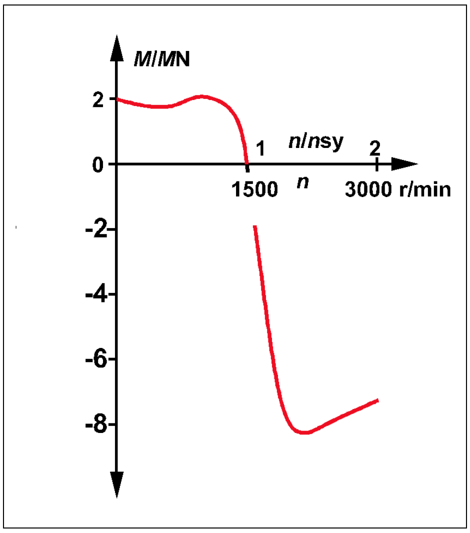


Fig. 5.3.8.4
Shape of the torque curve when switching from the lower to the higher pole number with a speed ratio of 2:1.
The ratio of the motoring pull-out torque to the regenerative pull-out torque in this case is about 1:4.

With regard to the effect of retardation on conveyed products by such pole-changing switching, it is advisable in some instances and sometimes even essential to reduce the rate of deceleration. This can be achieved simply by suitable modification of the existing contactor control.
When the motor is switched for 2-phase regenerative braking, with or without a series resistor, it must be ensured that single-phasing is effective only during the regenerative braking period. As soon as the regenerative braking period has ended, the motor must be reconnected to the three-phase lines L1, L2 and L3, otherwise part of the winding may become thermally overloaded (see section 5.2.4).
By reducing the decelerating torque, the mechanical load on the gearing and downstream transmission elements will be reduced. Details on the circuitry and torque curves may be found in [2.8].
Other possible ways of reducing the braking effect:

- for three-phase motors with a separate winding, the extra winding can, in certain limited cases, be adapted for use solely for regenerative braking. For this the frictional conditions, flywheel masses and speeds must be known precisely. This winding can then be designed for the application concerned and with this method no alterations to the control circuit are required.
- Regenerative braking is achieved by phase chopping whereby, during the retardation period, the voltage for the required rate of deceleration can be pre-set. This enables soft and time-controlled regenerative braking to be obtained.
- The conventional contactor control can be replaced by an ***electronic soft control inverter***.

5.3.9 Mechanical braking

The ***braking energy*** attacks the friction surfaces of the brake; this must be taken into account by selecting an appropriate brake with sufficient thermal capacity and wear reserves according to the size and design of the motor [2.22].

However, the brake may place an additional load on the motor and itself through ***delayed release.***

Due to mechanical and electrical inertia, response delays occur at each switching operation, that is to say when a mechanical brake is released and applied. Although the mechanical response times cannot be reduced in a certain design principle, that portion of the response times cause by magnetism can be decreased by switching technology. This applies in particular to brakes with D.C. solenoid releases, the field of which are known to build up and decay as an exponential function and which therefore have especially long response times compared to those of brakes with A.C. magnets.

Fig. 5.3.9.1 shows the theoretical and Fig. 5.3.9.2 the actual current curve when a solenoid is switched on.

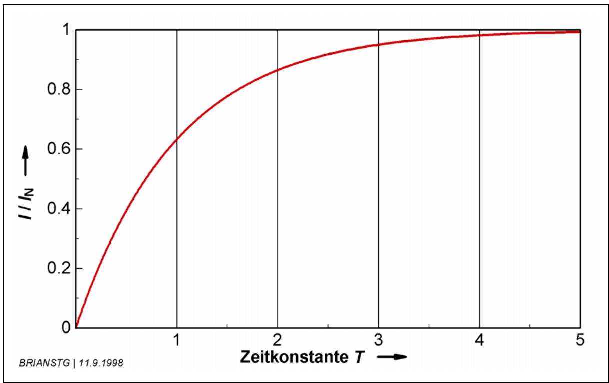


Fig. 5.3.9.1
Theoretical current curve when a D.C. solenoid is switched on

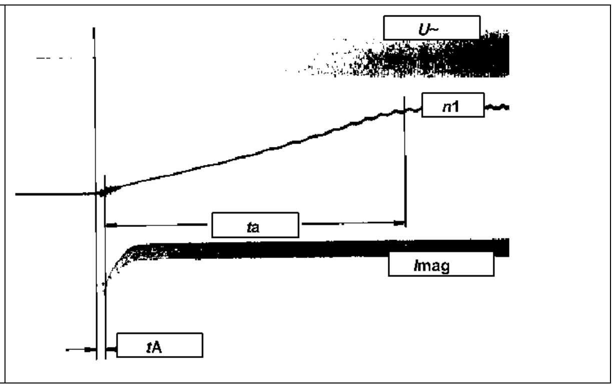


Fig. 5.3.9.2
Actual current curve when a a D.C. solenoid is switched on

U	Voltage	n_1	Speed
I_{magn}	Solenoid current	t_a	Run-up time
t_A	Response time of the brake		

The ***time constant T = L / R*** manifests itself more noticeably as the brake size increases.

The time constant T is reduced with ***high-speed excitation*** since the ohmic resistance R is increased by a series resistor.

This method has now been largely superseded by ***overexcitation***: the coil is connected to a multiple overvoltage for a limited period when it is switched on. The excessive current causes a correspondingly amplified magnetic force which accelerates the release process. The response time can be reduced to approximately 20 %, for example, by multiple overexcitation. Modern overexcitation rectifiers provide the temporary overvoltage and an electronic timing element. The reduction in the release response time can remove a considerable load from the motor and brake, above all for medium-size and large brakes which have particularly marked response times. If the motor's breakaway torque is greater than the braking torque, the motor will turn and the brake will be turned during the response time and thus subject to additional wear. If the braking torque is higher, the motor will remain locked and will be subjected to additional heating.

Fig. 5.3.9.3shows that the times are relatively high in comparison to the normal starting time t_a and can therefore and have a considerable effect on the balance of losses.

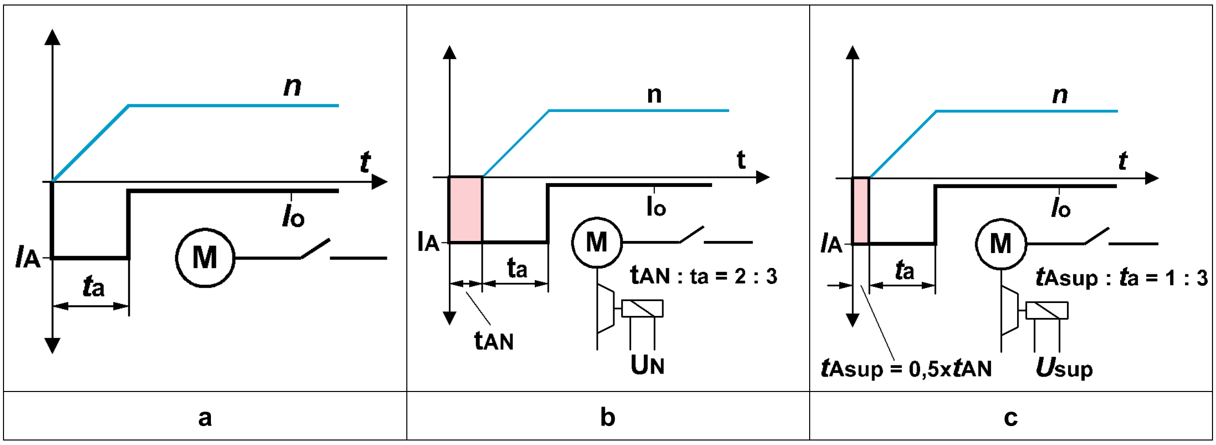


Fig. 5.3.9.3 Comparison of locking times
a) Without brake, run-up time t_a
b) Brake with overexcitation U_{sup}; locking time t_{Asup}
c) Brake with normal excitation U_N; locking time t_{AN}
Locking time and losses with overexcitation are only approx. 50% that of normal excitation

5.3.10 Frequency-controlled speed variations

By controlling the frequency alteration ("ramp"), it is possible both to make the starting and braking period as long or soft as possible and drastically reduce losses, hence the thermal load on the motor winding.

5.3.10.1 Starting

Where the motor is started using the mains supply, the rotating field speed n_{fld} almost instantaneously jumps to the synchronous speed n_{sy} whereas the rotor is only accelerated to its asynchronous speed after a starting time determined by the load and mass moments of inertia. The initially high slip speed Δn of between n_{fld} and n_{rot} causes the relatively high energy loss W_{rot} in the rotor (Fig. 5.3.10.1.1).
With frequency-controlled starting, the rotating field speed is only in advance of the rotor speed by the slip speed at which a sufficient acceleration torque can be generated.
The hatched area corresponds to the lost energy in the rotor – it is significantly lower for frequency-controlled starting than for direct-on-line switching from the mains supply (Fig. 5.3.10.1.2).
These considerations also apply to regenerative braking.

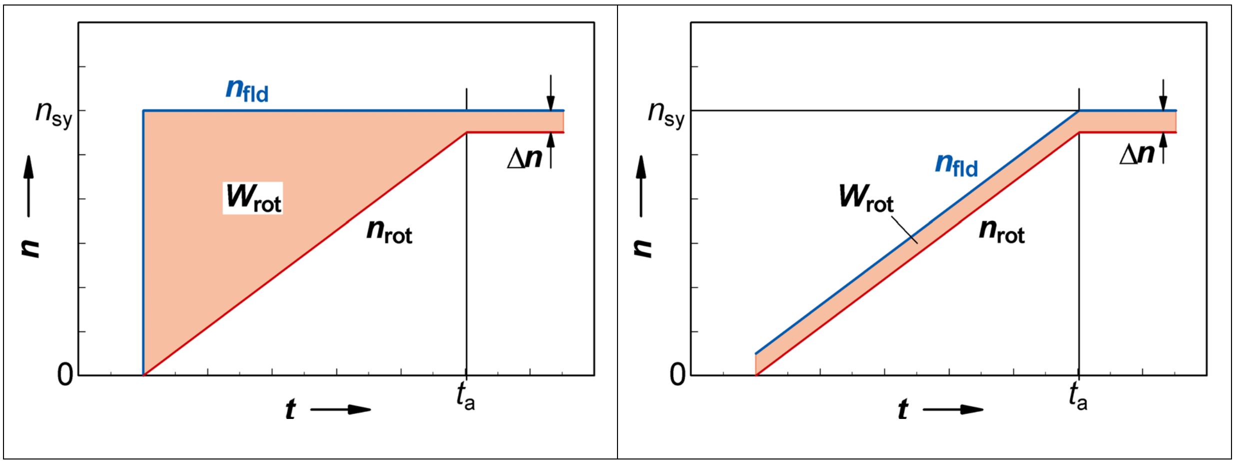


Fig. 5.3.10.1.1
Schematic diagram of the lost energy in the rotor W_{rot} for direct-on-line starting from the mains supply

Fig. 5.3.10.1.2
Schematic diagram of the lost energy in the rotor W_{rot} for frequency-controlled starting

5.3.10.2 Braking

The ***hyper-synchronous regenerative braking*** described in section 5.3.8.1 can also be used for retardation $n \Rightarrow 0$ if the frequency $f \Rightarrow 0$ is controlled. Frequency inverters make this possible.

The regenerated energy flows into the inverter. The blocking diodes in the input rectifier of the frequency inverter prevent power flowing back into the mains. To prevent undue charging of the intermediate link capacitor, which would force it to a dangerously high voltage, this regenerated energy must be dissipated by the ***brake-chopper*** through an auxiliary resistor where it will be converted to heat.

In specifying the brake-chopper it is necessary to check:

- ☐ maximum braking duty,
- ☐ average braking duty,
- ☐ equivalent continuous load on the basis of the duty cycle.

It is recommended that there be contact between the motor supplier and the inverter supplier.

The braking sequence is represented qualitatively in Fig. 5.3.10.2. In the period t_L from time zero to 1, the motor runs as an asynchronous machine with rotor speed n_{rot} which is slower than the rotating field speed n_{fld} by the slip speed Δn. Deceleration starts at time 1: the applied frequency, and hence the speed of rotation of the stator field, follows a pre-set ramp down to zero, under inverter control. The rotor speed and that of the driven masses – depending on the retardation effect of the load torque – initially remains at virtually its normal full value. This is therefore above the rotating field speed. Due to its hyper-synchronous speed Δn, the motor will develop a regenerative braking torque that will slow down the rotor over the braking period t_a.

At time 2, the frequency and speed of rotation of the stator field reach zero and the retardation effect then corresponds to D.C. braking. The rotor now runs on to time 4 uncontrolled, unless it is stopped at 3 by a mechanical brake (clamping brake).

The diagram assumes that the ramp will have been calculated beforehand to produce the required stopping time t_a and that the value of the parameters used will correspond to the actual conditions.

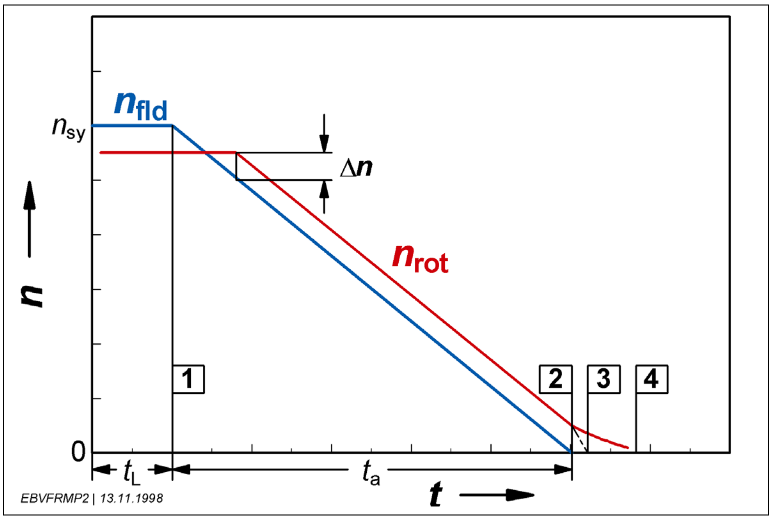


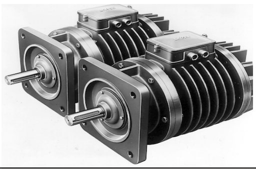
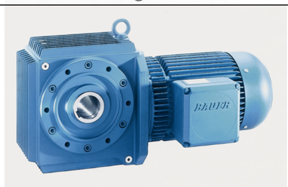
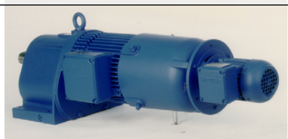
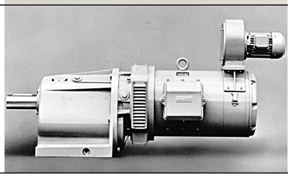
Fig. 5.3.10.2
Schematic diagram of frequency-controlled regenerative braking from speed n over time t

n_{fld}	Rotating field speed	1	Start of ramp
n_{rot}	Rotor speed	2	End of ramp
Δn	Slip speed	3	Application of mechanical clamping brake
t_L	Running time	4	Free-wheeling run-out
t_a	Braking period		

5.4 Cooling

Three-phase cage motors are cooled by air in the standardized range of ratings. The abbreviations for types of cooling (***IC Code***) are specified in EN 60034-6 / IEC 60034-6 [1.22].
Table 5.4 shows examples of common types of cooling.

Table 5.4 Types of cooling

IC code	Design	Characteristic	Type
IC410		Non-ventilated totally enclosed	Three-phase roller table motor
IC411		Self-ventilated totally enclosed	Three-phase cage motor with bevel gearing fitted
IC416		Independent fan totally enclosed	Three-phase cage motor with helical-gear unit fitted
IC06		Independent fan open-circuit, air-cooled	D.C. shunt motor with helical-gear unit fitted

5.4.1 Coolant temperature

The coolant temperature in standard motors must be equated with the ***ambient temperature***. The standardized limits and the effects of elevated ambient temperatures are discussed in section 4.2. Current-dependent overload protection is not suitable for this type of overload – the winding temperature must be measured directly (see section 6.2).

5.4.2 Restriction of the cooling air supply

Most electrical machines are cooled by air taken in from the environment by an external fan (surface-cooling, Fig. 5.4.2) or an internal fan (open-circuit cooling, Fig. 5.4.2.2).The ventilation channels may become fouled if the air contains a lot of dust (Fig. 5.4.2.3). This leads on the one hand to a reduction in cooling performance (i.e. increased winding temperature and the consequences of this) and on the other hand to degraded insulation condition. The ventilation channels and any downstream dust filters should therefore be cleaned regularly according to the level of dust.

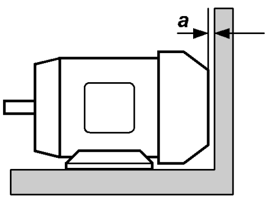


Fig. 5.4.2
Ensure that gap *a* is present on the air inlet.
In the standardized range: *a* at least 2 to 10 cm.1

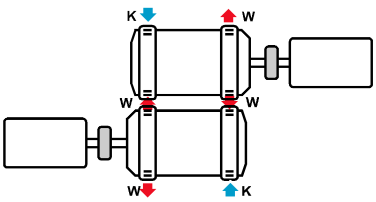


Fig. 5.4.2.2
Ensure the supply of ***cool*** air (K) !

Fig. 5.4.2.3
Fouled cooling ribs increase the degree of heating

5.4.3 Low speed

Normal three-phase cage motors are suitable for variable speed drives by fitting a static frequency inverter on the line side. This simple and widespread technique comes with the risk that the torque supplied by the motor will be also be demanded permanently or long-term in the low frequency (speed) range – i.e. with reduced cooling. A bimetal relay set to the rated current cannot signal any danger since the current determined by the torque flows virtually unaltered. The critical range lies below approximately 30 Hz (Fig. 5.4.3.1).
The reduction in the thermally permissible permanent torque resulting from additional losses caused by harmonics and from the speed-dependent cooling is represented by most manufacturers as simplified characteristic curves drawn from practical experience. A comparison (Fig. 5.4.3.1) reveals a relatively wide scatter range which can be explained by the different technical conditions and varying safety allowances.
This summary cannot and should not replace an individual analysis of the manufacturer's characteristic curves.

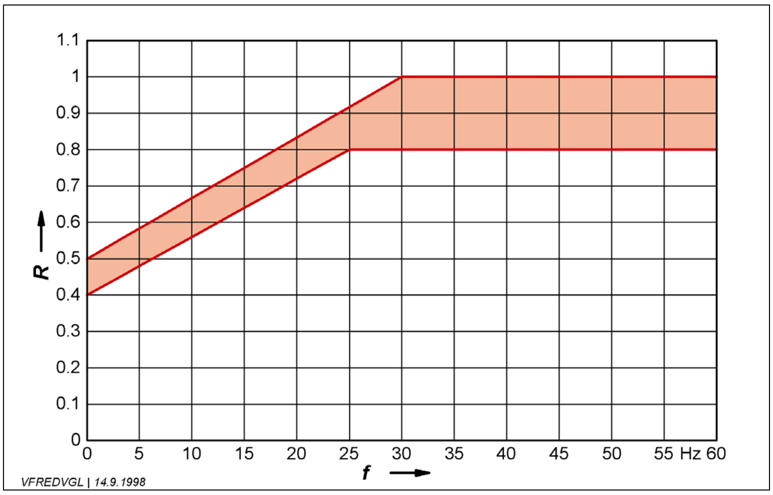


Fig. 5.4.3.1
Reduction factor *R* for the thermally permissible rated torque for self-ventilated cage motors (cooling type IC411) for continuous running duty S1

Converter feed *f* = 5 to 50 Hz

Scatter band for ten different manufacturers specifications and standards

If a mains-operated ***independent fan*** working separately of the inverter at a constant speed of rotation and cooling performance is used, the thermally permissible rated torque must not be reduced below the lower frequency range.
A choice must be made between the following at the design stage:
- ☐ a self-ventilated motor, the rated output of which has be increased to compensate for the reduction in torque determined by the cooling, and
- ☐ an independently-cooled motor of a reasonable size but with additional expenditure on the separate fan and its mains connection.

If main motor and fan motor are 4-pole, this produces benefits over a self-ventilated motor in terms of noise at frequencies above 50 Hz.
A decision based solely on cost can only be made on a case by case basis. The wide scatter band in Fig. 5.4.3.2 covers different manufacturer specifications and designs. On the whole, it reveals that a clear case can be made for self-ventilation (cooling type IC416) in the output range of up to 7.5 kW and for independent ventilation (cooling type IC416) above approximately 15 kW. The individual case must be checked in the output range between these two limit values.

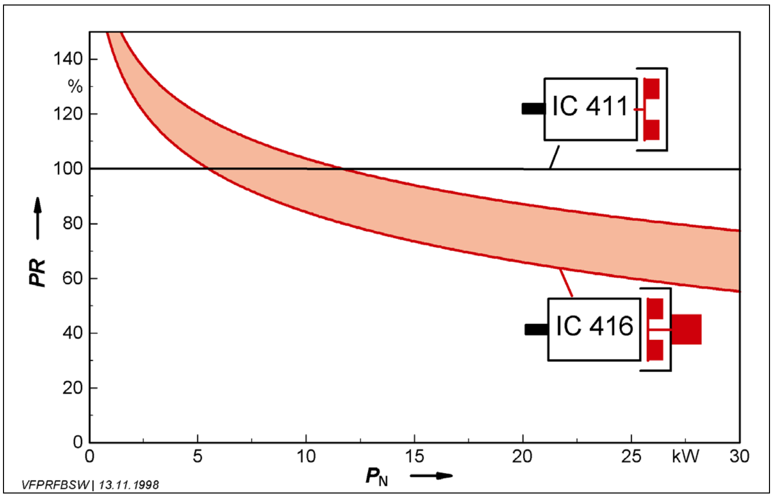


Fig. 5.4.3.2
Scatter band
for the relative price *PR*
of an independently-ventilated inverter-fed motor (IC416)
in comparison to
the enlarged self-ventilated model (IC411) for different designs and manufacturer specifications.

It is recommended to perform a separate price comparison in the transition range (approximately 5.5 to 15 kW 50 Hz rated output, 4-pole).

6 Protection of the motor winding

The ***increased current drawn*** in many cases of overloading, such as mechanical overload, overvoltage, undervoltage, frequent switching, locking, single-phasing, leads to an excessive winding temperature rise. However, there are other instances where the winding carries the normal rated current but can still be at risk. These occur when the ambient temperature rises excessively, the flow of cooling air is restricted or where an inverter-fed motor is operating at low frequency. The type of hazard and the degree of protection desired will determine which of the various methods of protecting the motor windings described below should be selected. In certain applications it may even be necessary to use a combination of two different protective devices.

6.1 Current-dependent overcurrent trips

6.1.1 Fuses

The fuses which must be installed in electrical machines are specified in the installation rules IEC 60364. A fuse rated at the same value as the motor's rated current can carry 1.2 times this current, which represents a dangerous overload on the motor. At six times the rated current, which may be drawn when the motor starts, a quick-acting type fuse should trip in 0.04 seconds and a delayed-action type in 0.5 seconds. In either case the fuse may blow before the motor is able to reach its rated speed safely (Fig. 6.1.1). Since, as a rule, only one of the three fuses will blow, the motor may continue to run on only two lines (a condition usually referred to as single-phasing or two-wire operation – see section 5.2.4) which is extremely dangerous for the motor when loaded. The following may be concluded:

- Fuses will safeguard the supply lines and parts of the electric installation, but provide no protection for the motor.
- To allow for the inrush current generated under direct-on-line switching, delayed-action fuses rated at approximately two to three times the rated current of the motor must be selected. The fuse protects the line in the event of a short-circuit; the motor protection relay provides the line with thermal overload protection (see highlighted traces 3+4 in Fig. 6.1.1). The installation rules must be observed in the selection of these separate protective devices.

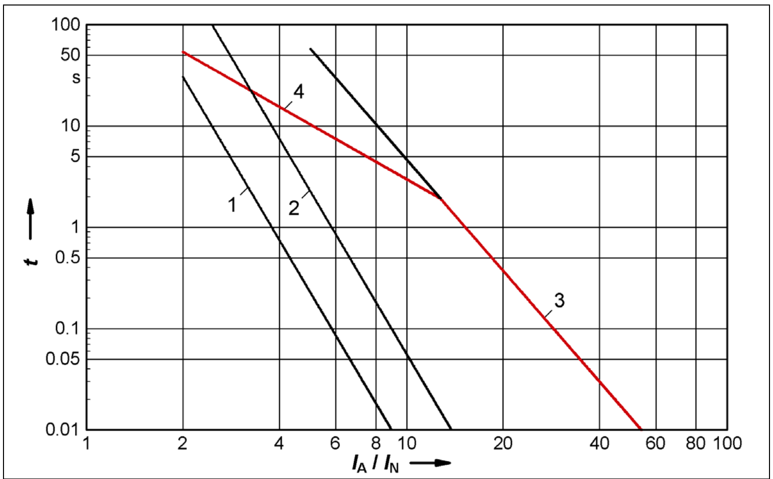


Fig. 6.1.1
Simplified trip characteristics of fuses and bimetal relays

Line	Overload device	Rated value	Trip time (approx.) in seconds
1	Quick-acting fuse	I_N	0.1
2	Delayed-action fuse	I_N	1
3	Delayed-action fuse	3 I_N	50
4	Bimetal cut-out	I_N	6
3	Delayed-action fuse	3 I_N	< 2
	Terminal short-circuit	$I_A/I_N > 10$	

6.1.2 Current-dependent delayed thermal overload relay

A bimetal strip in each supply line is heated either directly or indirectly by the current of the motor to be protected. As the current increases, more heat will be developed and the bimetal cut-out will operate

- as a bimetal cut-out by direct mechanical actuation through the action of a circuit-breaker triggering (motor protecting switch);
- as a bimetal relay via an auxiliary switch through the operation of the associated motor contactor.

The delay as shown by the characteristic curve for the bimetal element (Fig. 6.1.1) corresponds to the overload capacity of an electric motor. Thus, a relay will respond after approximately 2 hours at 1.2 times the rated current, but after only 6 seconds at 6 times the rated current (i.e. the starting current). During a normal starting cycle of less than say five seconds, the cut-out will not respond. If the motor is stalled (i.e. the rotor is locked with full mains voltage applied to the stator), the reaction time of the thermal overload protection is sufficiently short to prevent any damage to the motor windings.
In the case of star-delta starting, the overload protection must be connected in series with the phase windings and set to the ***phase current*** (Fig. 6.1.2).

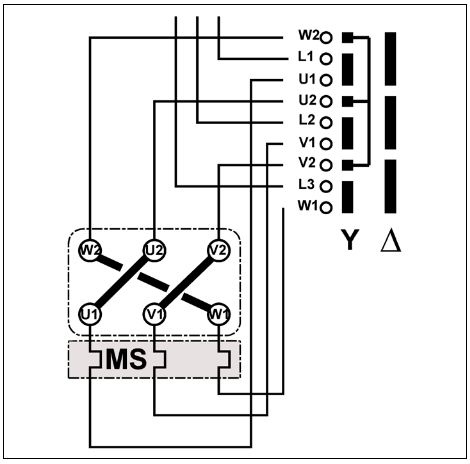


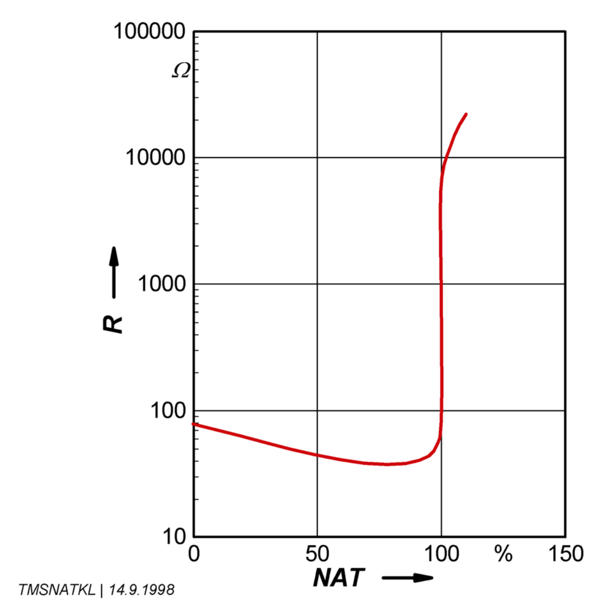
Fig. 6.1.2
Circuit diagram for Y-Δ connection with arrangement and rating of the bimetal cut-out MS
for the phase current $I_{strg} = I_N / 1.73$

6.2 Thermal motor protection by means of thermistors (TMS)

Current-dependent thermally-delayed motor starters (motor protecting switches with bimetal relays) are proven and cost-effective devices for providing electric machines with overload protection. It has become clear from the increasing use of electric drive in switched operation (duty type S4, for instance) that a relatively small device of this type ***is not a true thermal reflection*** of the motor (which has a far greater mass) and so it is inevitable that such devices trigger early.
The introduction of thermal machine protection (TMS) using thermistors in the mid-1960s was therefore very welcome amongst manufacturers and operators – the initial designation of “full motor protection” is a sign of the high expectations placed on the new system.
Failures which should have been prevented by a total motor protection system showed up the limitations of the new overload protection.
This section aims to describe the strengths and weaknesses of TMS and how full protection can be achieved in combination with tried and trusted motor protecting switches.

6.2.1 Operating principle of thermistor-type motor protection.

PTC temperature sensors **or** ***thermistors*** are temperature-dependent resistors with a positive temperature coefficient (PTC); in other words, they expand and undergo a sudden change in resistance (as shown in Fig. 6.2.1.1) at their ***nominal operating temperature*** NAT (e.g. 130 °C for motors with class B) insulation.



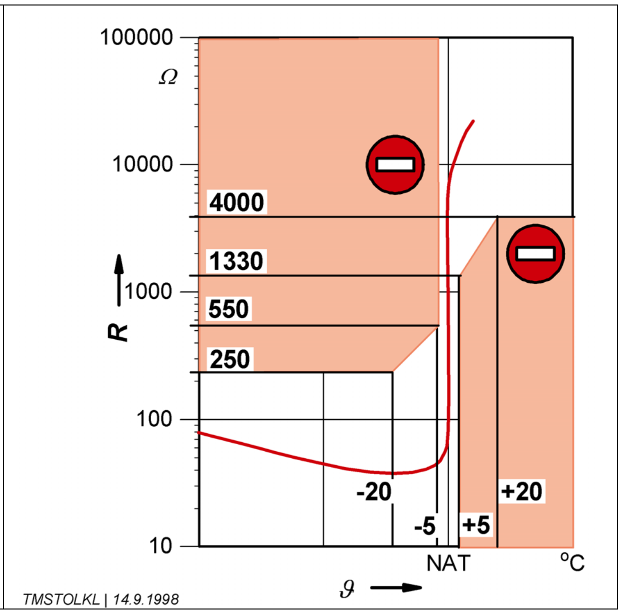


Fig. 6.2.1.1
Temperature resistance characteristic of a PTC thermistor
in accordance with IEC 60034-11-2 “Mark A”
NAT Nominal Actuation Temperature
PTC Positive Temperature Coefficient

Fig. 6.2.1.2
Permissible tolerance range for the characteristic of a thermistor in accordance with DIN 44081, table 1
NAT Nominal Actuation Temperature

The thermistors are connected in series with the relay coil of a circuit-breaker as shown in Fig. 6.2.1.3. When the tripping temperature has been reached or there is a line fault, the relay will respond and cause the motor to be disconnected from the supply.

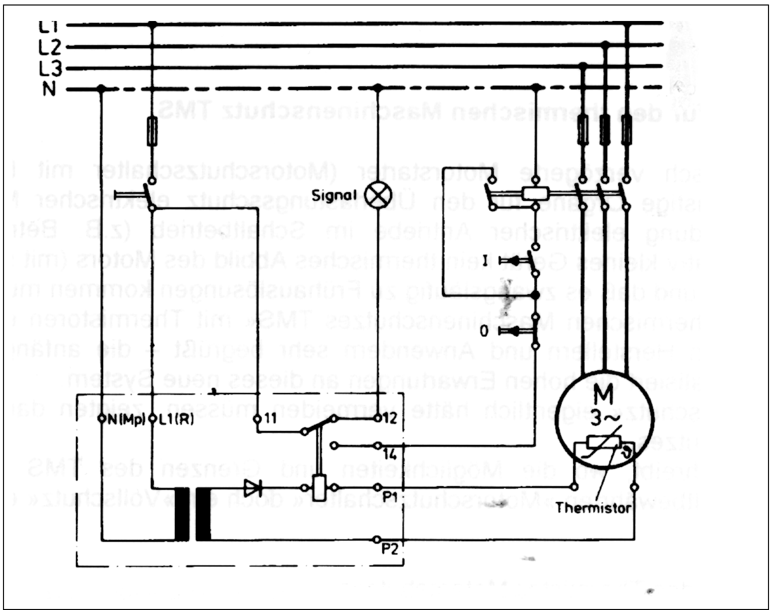


Fig. 6.2.1.3
Circuit diagram for thermal motor protection (TMS) using PTC thermistors

The following rules should be noted when checking the principle of operation of thermistors:

- ☐ **Continuity**
  Maximum D.C. 2.5 V per sensor.
  Higher voltages (e.g. buzzers, indicator lamps) can result in destruction of the thermistor.

- ☐ **Insulation**
  A.C. test voltage in accordance with EN 60034-1 / IEC 60034-1 between the sensor circuit and the motor winding electrically bonded to the frame and connected to earth.
  The sensor circuit must be earthed for the motor winding's insulation test to prevent damage from capacitive charging.

- ☐ **Resistance at room temperature**
  Values of $R \leq 250\ \Omega$ per sensor are permissible in accordance with the standard; experience shows that the reading for three sensors connected in series lies between 100 and 600 Ω.
  Maximum measuring voltage D.C. 2.5 V per sensor.

- ☐ **Nominal actuation temperature (NAT)** (Table 6.2.1)

  Table 6.1 Designation and colour-coding of nominal actuation temperatures in accordance with DIN 44081

NAT °C	Colour code	NAT °C	Colour code	NAT °C	Colour code
60	white/grey	110	brown/brown	150	black/black
70	white/brown	120	grey/grey	155	blue/black
80	white/white	130	blue/blue	160	blue/red
90	green/green	140	white/blue	170	white/green
100	red/red	145	white/black	180	white/red

- ☐ **Actual response temperature**
  It is recommended that the following method be used if the resistance thresholds specified in Fig. 6.2.1.2 are observed but doubt remains as to the actual response temperature:
  The stator and its winding are slowly heated in a drying oven or by connection to a suitable heating voltage. The temperature rise should not be greater than about 2 K/min near the NAT. The actual response temperature should not deviate from the NAT by more than ± 5 K.

6.2.2 Installation of the temperature sensor

The function of the TMS depends largely on the correct installation of the sensor. If possible they should be built into the ***hottest spot*** of the motor winding and in good thermal contact with the winding.

6.2.2.1 Surface-ventilated machines (e.g. IC411, IC416)

The primary cooling circuit created by the agitator blades on the rotor (internal air movement around the end windings) is generally not very effective. Heat flows mainly over the slots to the laminated core, from where it is conducted to the surface of the enclosure which is usually ribbed. The hottest spot on this type of machine is in the end winding on the side facing away from the external fan – generally the A or D-end side (Fig. 6.2.2.1).

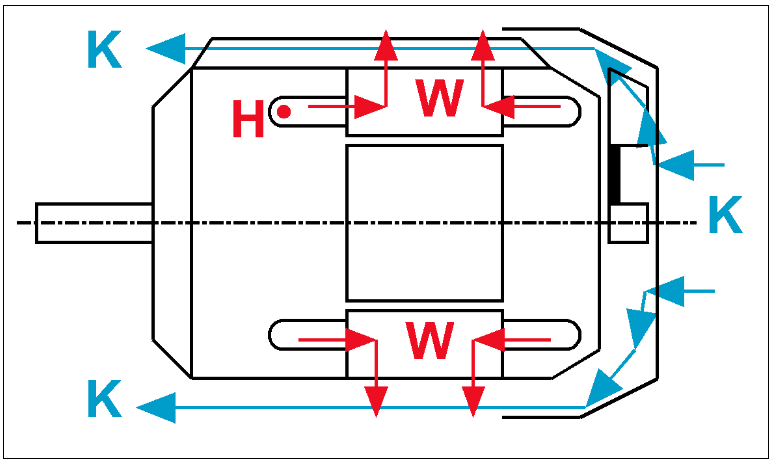


Fig. 6.2.2.1
Heat flow (W), cooling air flow (K) and hottest spot (H) on surface-ventilated machines
(e.g. IC411, IC416)

6.2.2.2 Open-circuit air-cooled machines (e.g. IC01, IC06)
The end windings are intensively ventilated by the cooling air flow. Heat flows mainly from the slot to the end winding. The hottest spot on this type of machine is roughly the centre of the slot (Fig. 6.2.2.2). If the conductor assemly in the slot prevents the sensor from being fitted in the slot, the end winding must be positioned on the exhaust side and the sensor fitted such that it is not directly affected by the airflow.

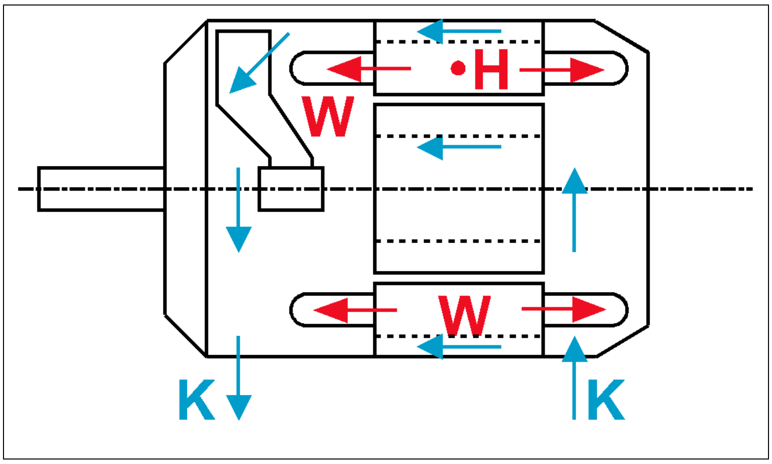
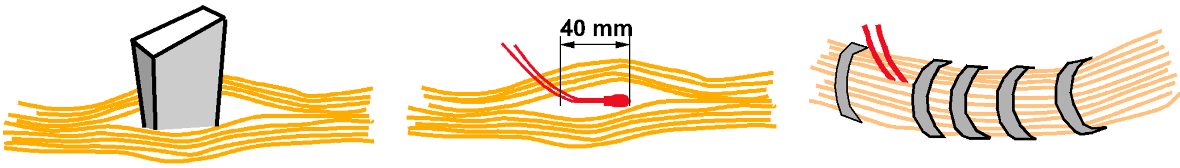


Fig. 6.2.2.2
Heat flow (W), cooling air flow (K) and hottest spot (H) on open-circuit air-cooled machines
(e.g. IC01, IC06)

6.2.2.3 Embedding in the end winding

Temperature sensors must be embedded in the end winding parallel to the winding wires when the winding is manufactured. According to the specifications of one sensor manufacturer [2.20], the brush shunts should be embedded to a depth of 30 to 40 mm (Fig. 6.2.2.3). Excessive mechanical stress on sensors must be avoided when the end winding is formed.



Spreading out the end winding | Inserting the thermistor | Banding the end winding

Fig. 6.2.2.3
Procedure for fitting thermistors in the end winding according to manufacturer specifications [2.20]

6.2.2.4 Retrofitting on the end winding

This type of installation should be restricted to exceptional circumstances only as it provides insufficient heat transmission.
The excess temperature for different types of installation compared to the standard method of embedding the thermistors has been found in a basic test (Table 6.2.2.4).

Table 6.2.2.4 Influence of the installation type on the excess temperature

Installation type	Increase in the response temperature K
Using heat transfer compound	30
Banded on without heat-conducting compound	50
Banded on with unsuitable plastic compound	80

We recommend the following in ***exceptional circumstances*** where the retrofitting of thermistors to the end winding cannot be avoided:

- ☐ Use heat transfer compound to improve heat transfer,
- ☐ Reduce the NAT by 10 to 20 K below the standard values for embedding thermistors (see section 6.2.6).

6.2.3 Temperature change in the winding and sensor

The electrical insulation between the sensor and winding retards the transfer of heat from the copper wire to the thermistor. This results in a temperature difference, the precise magnitude of which depends on the type of duty and overloading.

6.2.3.1 Slow temperature rise (e.g. duty type S1)

In the case of duty type S1, equilibrium temperature is only reached after 2 to 8 h depending on the size and ventilation of the motor. The difference in temperature (temperature overrun) between the winding and the thermistor is negligible (Fig. 6.2.3.1).

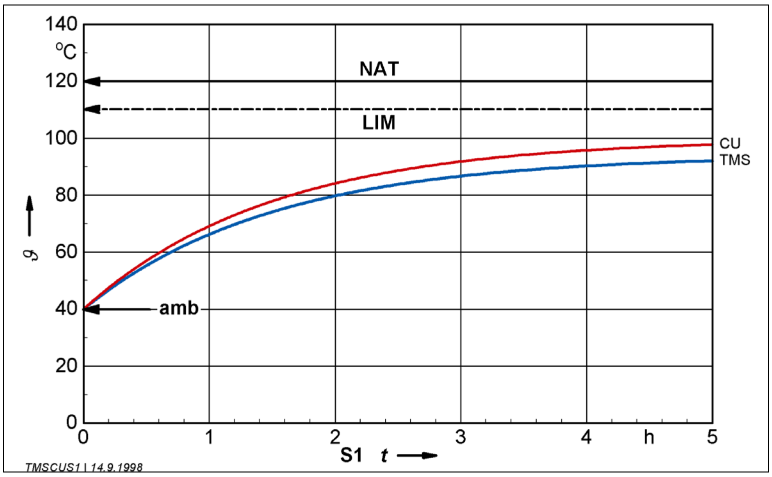


Fig. 6.2.3.1
Temperature change ϑ in the copper wire (CU) and thermistor (TMS) compared to the limit temperature (LIM) and nominal operating temperature (NAT) continuous running duty S1 – explosion-proof class EEx e II T3 – thermal classification B – ambient temperature (amb) 40 °C

In the event of severe overloading (e.g. at 1.5 to 2 times the rated current), the ***temperature overrun*** of the winding is indeed slightly higher but remains within the thermal overload capacity of good insulation as long as overloading does not occur too frequently.
Overloading is detected by the TMS when the motor is running.

6.2.3.2 Rapid temperature increase

Three-phase asynchronous motors are exposed to the starting current if the rotor locks (i.e. in the event of a “short-circuit”). The starting current may be roughly 400 to 800 % of the rated current depending on the size, number of poles and design of the motor. The heat build-up in the copper wire – related to the square of the current – increases very rapidly; its curve may be considered linear during the first seconds as shown in Fig. 6.2.3.2. The temperature of the thermistor follows after a response time T_K governed by the resistance to heat transfer resistance, i.e. the thickness of the insulation. Values of 3 to 6 (8) seconds are common.

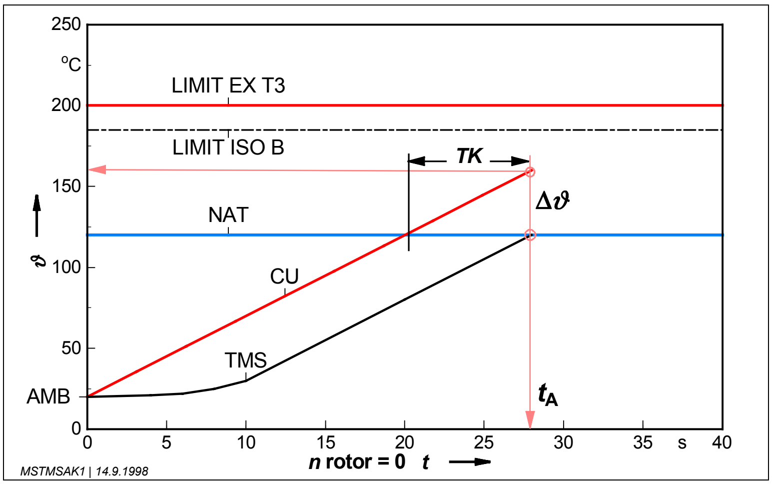


Fig. 6.2.3.2
Temperature change in the winding wire (CU) and in the thermistor (TMS) under high overloading – e.g. with the rotor locked ($n_{rotor} = 0$)

AMB	Ambient temperature	$\Delta\vartheta$	Temperature overrun
ϑ	Temperature	LIMIT ISO B	Limit for temperature class B
NAT	Nominal operating temperature	LIMIT EX T3	Limit for temperature class T3
TK	Response time		

The winding temperature when the TMS responds is thus always higher than the NAT.
This temperature overrun $\Delta\vartheta$ is dependent on
- ☐ ***the response time T_K,***
- ☐ ***the rate of rise $v = \Delta\vartheta / T_K$.***

6.2.4 Influence of the response time T_K

A rate of temperature increase of v = 5 K/s can be expected at a starting current density i_A = 30 A/mm². If we assume a poor response time of T_K = 8 s, the temperature overrun will be $\Delta\vartheta = T_K \cdot v$ = 8 s · 5 K/s = 40 K. If the sensor's insulation is “improved” such that the response time rises to double its original value, i.e. T_K = 16 s, the temperature overrun will be 80 K. Cut-out will not therefore occur until a temperature approximately 80 K above the nominal actuation temperature (NAT) of the sensor is reached (Fig. 6.2.4).

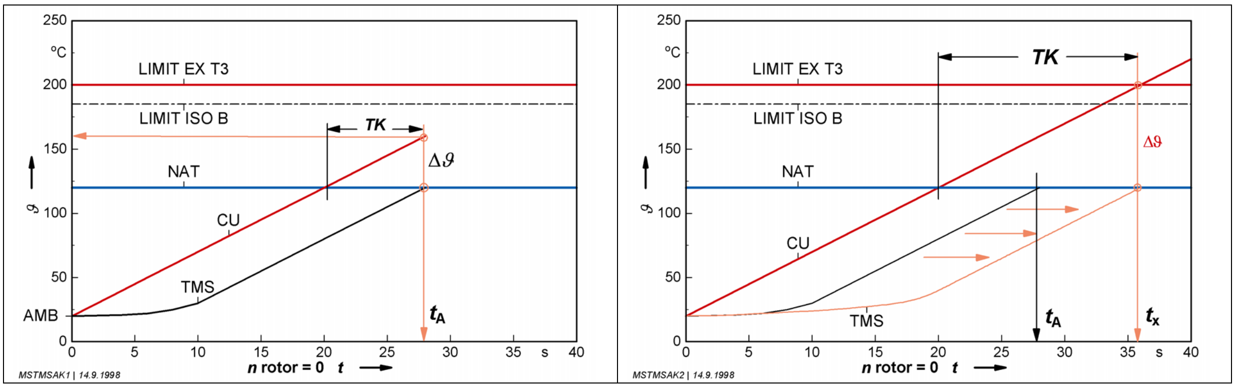


Fig. 6.2.4 Temperature overrun $\Delta\vartheta$ in the winding (CU) of a highly power-per-space-rated three-phase motor at standard response time (T_K = 8 s) and a poorer response time (T_K = 16 s) than the nominal operating temperature (NAT) of the thermistor (TMS)
The rate of temperature increase v is approximately 5 K/s in both cases

It follows from this that:
The response time should be kept as short as possible by using the thinnest foils or heat shrink sleeves for the sensor's insulation.

6.2.5 Influence of the current density

The ***rate of rise*** of the temperature is directly dependent on the *starting current density* i_A (Fig. 6.2.5.1).

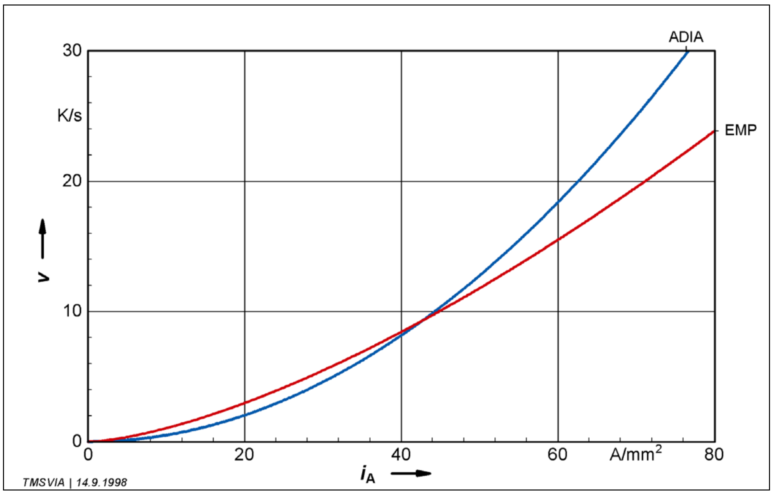


Fig. 6.2.5.1
Guide values for the rate of rise *v* of the winding temperature as a function of the short-circuit current density i_A

ADIA Theoretical value as a result of adiabatic heating [8]

EMP Empirical value as the average taken from many measurements (Danfoss Bauer GmbH)

The following results are obtained for a standard response time T_K = 8 seconds

- ☐ a temperature overrun of approximately 40 K at normal current densities of about 30 A/mm²,
- ☐ a temperature overrun of approximately 120 K at extreme current densities of about 60 A/mm², for example (Fig. 6.2.5.2).

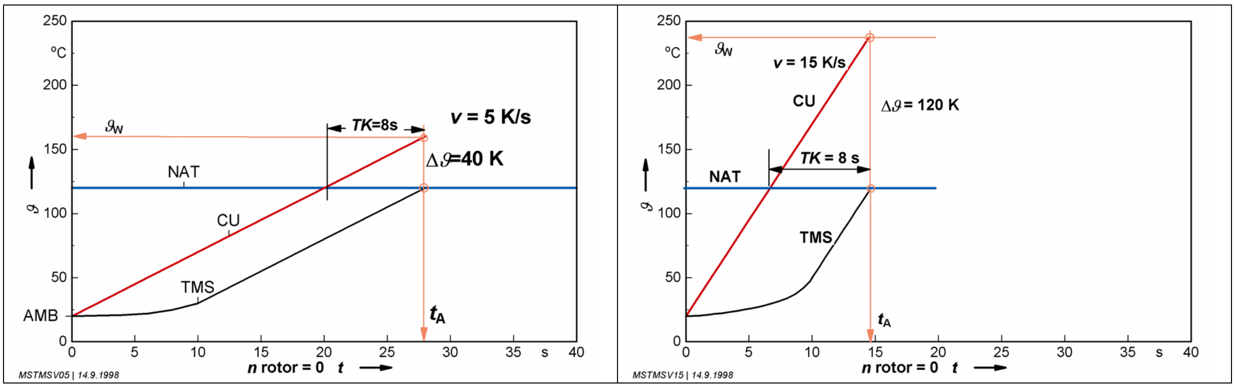


Fig. 6.2.5.2 Temperature overrun $\Delta\vartheta$ in the winding (CU) of a three-phase motor at standard (*v* = 5 K/s) and extreme rate of temperature increase (*v* = 15 K/s) against the nominal operating temperature (NAT) of the thermistor (TMS)
The response time (T_K) is about 8 seconds in both cases

It follows from this that:
Current densities above approximately 40 A/mm² will cause a temperature overrun $\Delta\vartheta$ > 50 K. Higher values jeopardize the winding insulation.
Thermistors cannot provide "stand-alone protection" or "full protection" in such cases.
A combination of thermistor and current-dependent bimetal cut-out (motor protecting switch) is recommended. The latter should be set to trigger after no more than 15 seconds of a rotor locking (i.e. at a current of I_A).

6.2.6 Selection of the nominal actuation temperature (NAT)

No generally applicable rules can be specified for relating the NAT to a particular thermal classification since the temperature conditions, thermal conductivity and the location are too varied with different types of machine. Therefore, IEC 60034-11 merely specify the maximum permitted winding temperature that may be reached after the TMS has responded. The values for Category 1 embody a higher factor of safety than for Category 2 which should therefore only be adopted in the full knowledge of operating conditions (Table 6.2.6.1).

Table 6.2.6.1 Guide values for the coordination of the NAT with the thermal classification and the limiting temperature after the response of the sensor in accordance with IEC 60034-11

Category	Limit temperature in °C after the response of the temperature sensor for thermal classification		
	B	F	H
1	145	170	195
2	165	190	215

The guide values for the NAT in Table 6.2.6.2 correspond to the average of various manufacturers' data and have been found satisfactory in practice for surface-cooled motors.

Table 6.2.6.2
Guide values for the selection of the NAT (nominal actuation temperature) for temperature class B, F and H surface-ventilated (IC4X) and open-circuit air-cooled (IC0X) machines

Cooling type	Function	NAT in °C for thermal classification		
		B	F	H
IC 4X (surface-ventilated)	Alarm	120	140	160
	Trip	140	160	180
IC 0X (open-circuit air-cooled)	Alarm	110	130	150
	Trip	130	150	170

6.3 Thermal releases (thermostats)

Small bimetal-controlled switch mechanisms operate a control contact suddenly on reaching the response temperature. They will either break the main motor circuit directly in the case of small-power motors (rated value of 1 A, 250 V, for example) or act on the control circuit in the case of larger motors. Although it has been possible to reduce the outer dimensions of the original "button" thermostats over the course of many years of development (Fig. 6.3), they have several disadvantages over thermistors:

- greater mass, therefore retarded "thermal response" with risk of damage to the winding in the event of rapid temperature increase, cause for example by locking the rotor (see section 6.2.4).
- long cooling time before the thermostat can be "reset",
- large dimensions, therefore difficult to install in small motors.

For these reasons, thermostats have only limited applicability compared to thermistors.

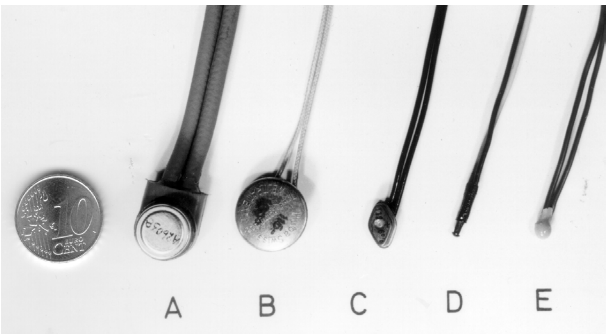


Fig. 6.3
Size comparison between thermostats of various types (A, B, C) with thermistors (D, E)

6.4 Resistance thermometers

In some applications – particularly those involving larger machines– is it necessary not only to limit the temperature of the winding or a bearing but also to ***measure*** this and compare it visually or automatically with a setpoint value. The relation between temperature and the resistance of metal elements is virtually linear, making them particularly suitable for this purpose. Platinum sensors conforming to EN 60751 and described in full in [3.8] are preferred due to their high chemical resistance and the good reproducibility of their electrical properties. The characteristic curve of a PT 100 temperature sensor is shown in Fig. 6.4.

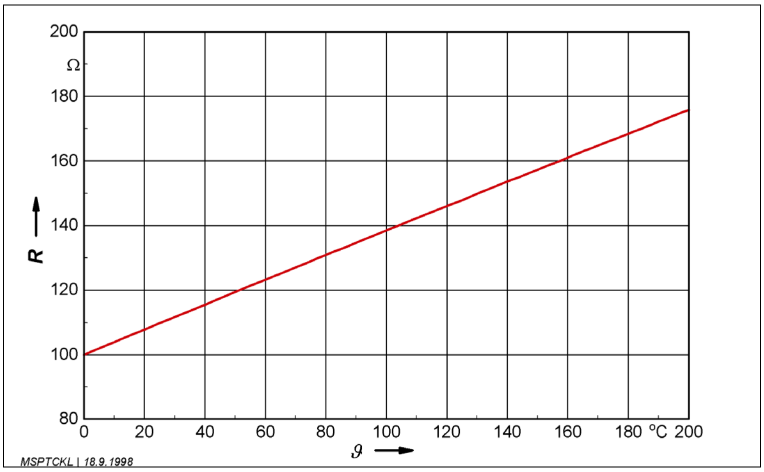


Fig. 6.4
Resistance R as a function of the temperature ϑ for a PT 100 platinum resistance thermometer

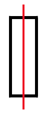
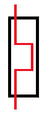
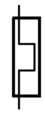
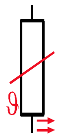
6.5 Electronic motor protection relay

The thermal characteristics of a motor can be simulated with these relays; in this way the tripping characteristics largely correspond to the thermal loading capacity of the motor. The following can also be monitored: phase failure, mains symmetry, short-circuit to earth, overload, resetting readiness [2.10]. These relays require careful calibration when commissioned according to parameters which the motor manufacturer can provide. Their relatively high cost currently restricts their use to larger machines, high-voltage motors or isolated cases where high availability is demanded [2.2].

6.6 Provisions for protecting against different types of overload

Table 6.6.1 summarizes common types of overload and the provisions for protecting different equipment. Fuses have been included in the comparison to highlight the fact that they provide protection for the line only, not for the motor.

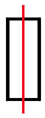
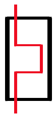
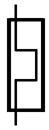
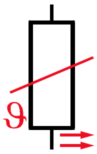
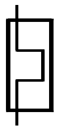
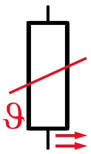
Table 6.6.1 Protective effect of conventional motor protection devices

Type of overload	Protective element				
					
Overcurrent $I \leq 2 \cdot I_N$	□	■	■	■	■
Switching duty $Z \leq 30$ c/h	□	♦	♦	■	■
Switching duty $Z > 30$ c/h	□	□	□	■	■
Heavy starting duty $t_a > 6$ s	□	■	■	♦	■
Locked rotor at $i_A \leq 40$ A/mm²	♦	■	■	■	■
Locked rotor at $i_A > 40$ A/mm²	♦	■	■	♦	■
Single-phasing *)	□	♦	■	■	■
Voltage fluctuation $\Delta U > \pm 10$ %	□	■	■	■	■
Frequency fluctuation $\Delta f > \pm 5$ %	□	■	■	■	■
Ambient temperature $\vartheta_{amb} > 50$ °C	□	□	□	■	■
Poor cooling caused by fouling etc.	□	□	□	■	■
Inverter duty below permissible frequency ranges	□	□	□	■	■

Explanation of the protection provision:
- □ No protection
- ♦ Partial protection
- ■ Full protection

I	Actual overload current
I_N	Rated current of the motor
Z	Switching cycles per hour; in general, no false tripping is to be expected at up to 30 c/h; false tripping of the bimetal relay cannot be ruled out at more than 30 c/h
t_a	Run-up time; if longer than 6 seconds, false tripping of the bimetal relay must be expected – use a saturable current transformer
i_A	Current density resulting from starting current I_A
*)	Windings in Δ-connection are particularly at risk if a phase failure sensitivity relay is not used.
ΔU	Voltage deviation in the form of a mains fluctuation; see EN 60034-1 / IEC 60034-1, 12.3
Δf	Frequency deviation in the form of a mains fluctuation; see EN 60034-1 / IEC 60034-1, 12.3
ϑ_{amb}	Ambient temperature

Table 6.6.2 Key to the protective elements in Table 6.6.1

Symbol	Explanation
	Delayed-action fuse Rated value (1.6 to 2.5)·I_N
	Current-dependent delayed thermal overcurrent relay (bimetal relay = motor protecting switch) Setting current $I_E = I_N$
 2ph	Current-dependent delayed thermal overcurrent relay (bimetal relay = motor protecting switch) with phase failure sensitivity Setting current $I_E = I_N$
	TMS thermal motor protection (thermistor relay) Response time $T_K < 6$ s
 2ph	Current-dependent delayed thermal overcurrent relay (bimetal relay = motor protecting switch) with phase failure sensitivity Tripping characteristic TI Setting current I_E : 1.5 $I_N < I_E <$ 0.3 I_A as low as possible, but max. 0.3 I_A
+	combined with
	TMS thermal motor protection (thermistor relay) Response time $T_K < 6$ s

7 Mounting

The choice of the correct installation location, mounting type and power transmission components are decisive factors in determining the service life of a drive unit.

7.1 Installation location

The drive unit should be installed such that it is as vibration-free as possible. In degree of protection IP54 in accordance with [1.1], drive unit is dust-protected and secure against penetration by spray water; in degree of protection IP65, the drive unit is dust-tight and secure against penetration by water from a jet (see clause 3). If the drive unit is intended for outdoor installation, corrosion protection must be provided by several coats of a durable paint. Special regulations must be observed where the location is subject to abnormal operating conditions (such as prolonged water drenching, high ambient temperatures above 30 to 40 °C, danger of explosion). The intake of fresh air must not be obstructed by poor installation or fouling (see clause 5.4.2). Intensive and prolonged exposure to solar radiation must be prevented by the provision of a protective roof.

7.2 Type of construction and mounting arrangement

The standard differentiates between the ***type of installation*** (e.g. mounting by foot or flange) and the ***mounting arrangement*** (e.g. horizontal, vertical or fixed to the wall; Tables 7.2.1 and 7.2.2).

Table 7.2.1 Examples of common mounting arrangements of the foot type

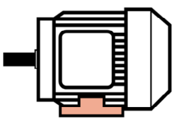
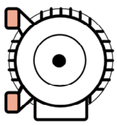
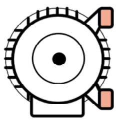
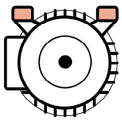
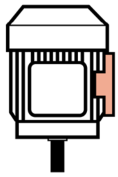
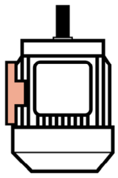
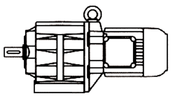
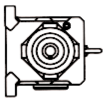
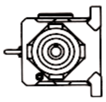
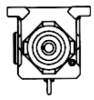
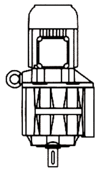
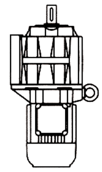
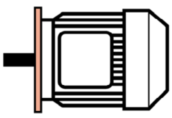
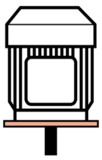
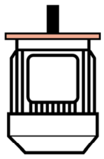
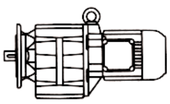
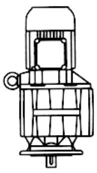
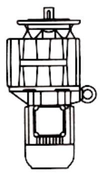
IM B3	IM B6	IM B7	IM B8	IM V5	IM V6
IM 1001	IM 1051	IM 1061	IM 1071	IM 1011	IM 1031
					
					

Table 7.2.2 Examples of common mountings of the flange type

IM B5	IM V1	IM V3
IM 3001	IM 3011	IM 3031
		
		

The design and manufacture of standard motors are generally the same for all mounting arrangements. The ***lubricant quantity*** on geared motors is the only, but important, exception to this. The lubricant is filled to the optimum level at the works for the mounting specified in the order and this data is marked on the rating plate as an ***IM code***; this must be adjusted by topping up or draining off the appropriate quantity of lubricant if the arrangement is altered at a later stage (Figures 7.2.3 and 7.2.4). The quantity of lubricant filled at the works and the setpoint quantity can be found in the accompanying documentation.

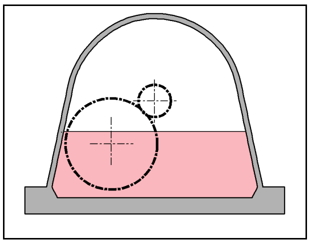
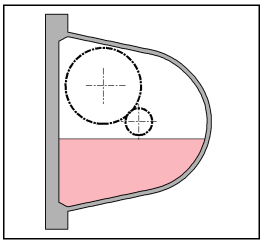


Fig. 7.2.3
Optimum lubricant level for B3 mounting

Fig. 7.2.4
Risk of dry-running if the mounting arrangement is subsequently changed from B3 to B6 without adjusting the quantity of lubricant



7.3 Alignment

Machines and couplings must be aligned such that the centre axes of the shafts run parallel without being ***offset*** (Figures 7.3.1 and 7.3.2). The faster the shafts are rotating and the more rigid the couplings is, the more serious the consequences of faults may be for the service life of the bearings.
This rule tells us that geared motors generally require less effort to run than standard motors – particularly if couplings are chosen which permit relatively large offset (see clause 7.6). However, the maximum offset permitted for the clutches should never be exploited in view of the potential load on the bearings.
The optical means available today for which use laser beams and computers to enable precise and simple alignment of the shafts are therefore only required in special cases but make this task much easier (Fig. 7.3.3).

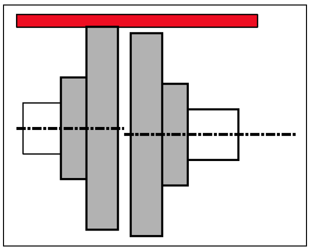
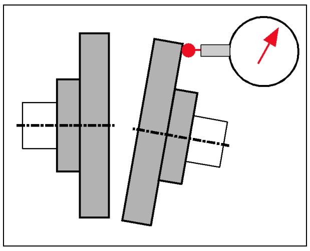


Fig. 7.3.1
Checking the shaft alignment using a hairline gauge

Fig. 7.3.2
Checking the angular offset using a dial gauge



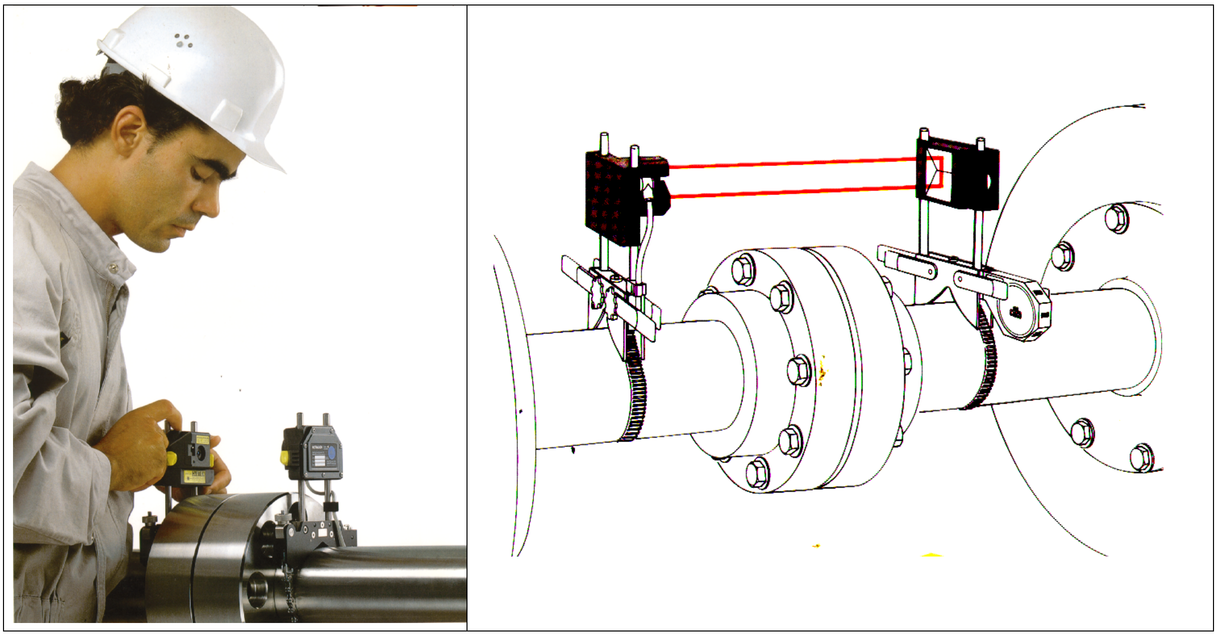


Fig. 7.3.3
Aligning the shafts using a laser and computer (Source: ROTALIGN Prüftechnik AG, Ismaning)

7.4 Securing

Depending on their transmission ratio, geared motors develop higher torques and forces than high-speed motors of a comparable output. The securing fixtures, base structure and torque bracing must be adequate for the high forces to be expected during operation and starting and be secured sufficiently against working loose.
Fig. 7.4.1 provides guide values for the forces to be expected on the fixings during starting under the following conditions:

- ☐ observance of the minimum pitch circle diameters as specified in section 7.7,
- ☐ full breakaway torque flows across the gear unit resulting in loading (e.g. in the event of a high factor of inertia *FI* or locking),
- ☐ no additional forces resulting from mass action,due, for example, from play in the power transmission components.

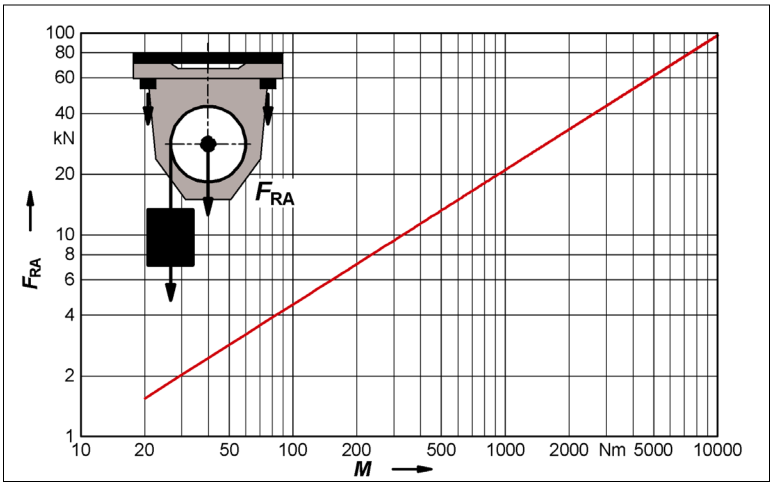


Fig. 7.4.1
Guide values for the forces F_{RA} to be expected when starting up against large external masses on geared motor fixings, plotted against the rated torque *M*

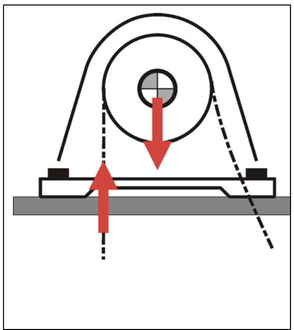
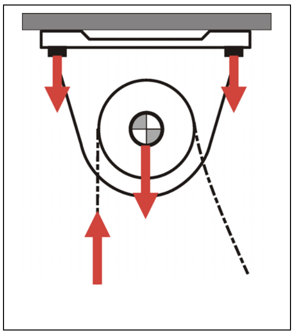


Fig. 7.4.2
Satisfactory mounting of a geared motor
Grey cast iron enclosure subject to pressure,
low strain on the securing bolts

Fig 7.4.3
Poor mounting of a geared motor
Grey cast iron enclosure subject to tensile forces,
high strain on the securing bolts



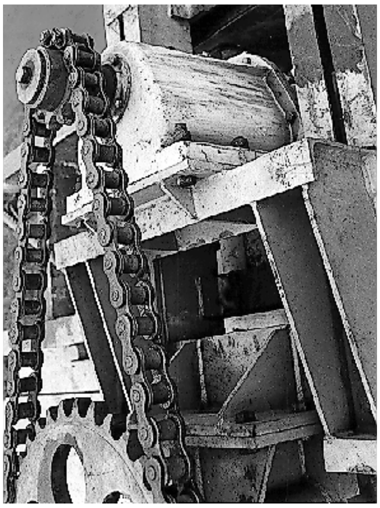
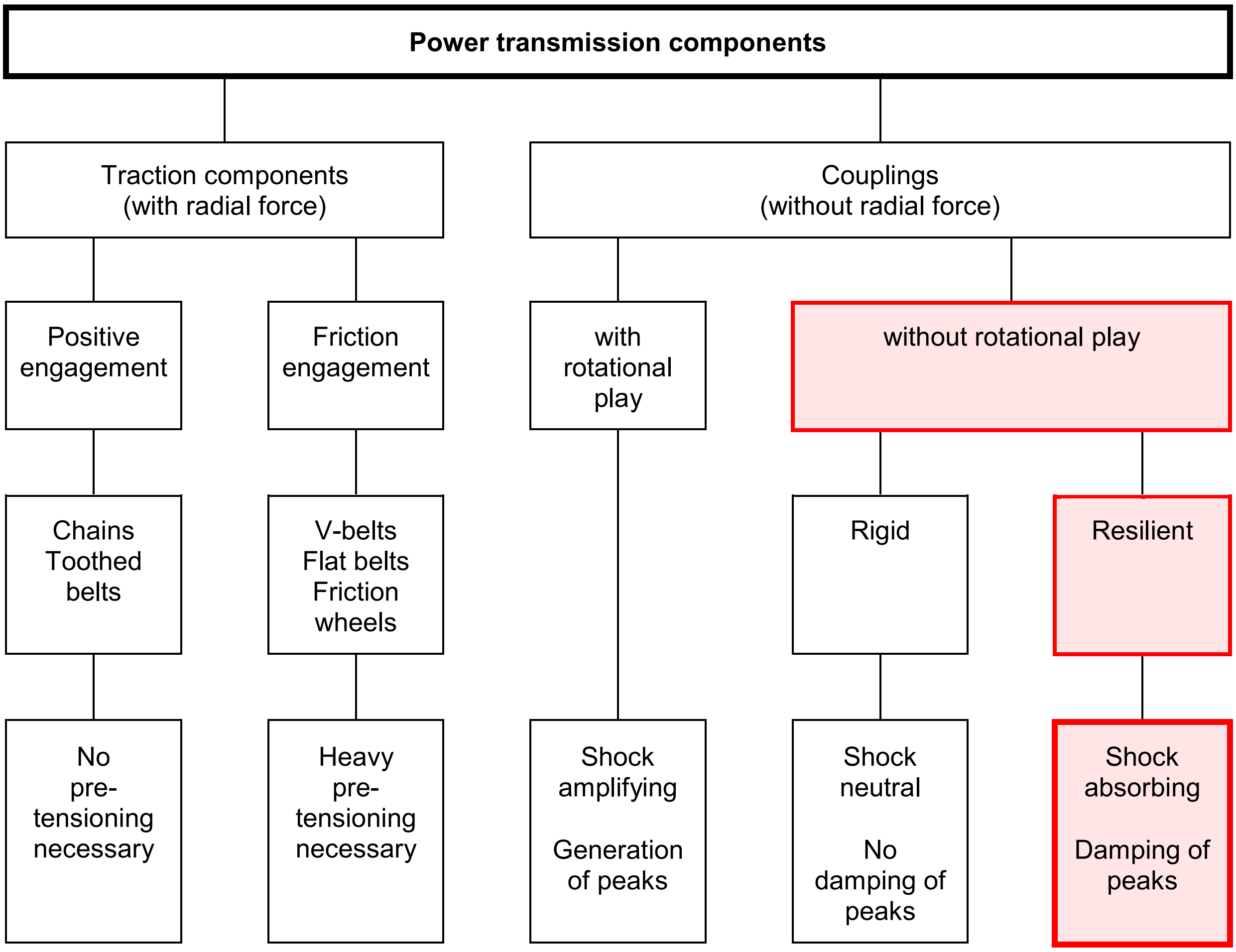


Fig. 7.4.4
Example of application of a geared motor on construction machinery with a satisfactory mounting to absorb the high radial forces generated by the chain pulley block

8 Selection of the power transmission components

The torques developed by a drive are transferred to the driven machinery in various ways. The mounting position or the need for an auxiliary reduction ratio may inevitably dictate the choice of power transmission component.
Power transmission components with play (chains, claw couplings) can lead to dangerous peak torques generated dynamically, above all in switching duty. The use of a zero-play highly resilient coupling is strongly recommended for drives of this type.



8.1 Couplings

Where slow speed drives (e.g. geared motors) are used, high driving forces are required. In case of direct coupling these external forces are applied as a pair and therefore do not additionally load the shaft extension and the bearings of the output shaft (Fig. 8.1.1).

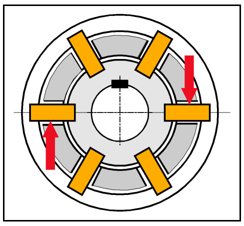


Fig. 8.1.1
There is no overhung effect on the shaft resulting from the pair of forces in a coupling

Many different designs and makes of these power transmission components are available on the market. The “Coupling Atlas” produced by *A. Schalitz* (sadly out of print) provides an exhaustive overview and useful classification system of this subject.
Table 8.1.4 shows a representative list of ten systems and evaluates each in the light of many years of practical experience. Because each drive scenario poses different conditions, the evaluations can only be considered ***unbinding recommendations***. ***Endurance*** (e.g. the service life in switching duty) is not evaluated.
An evaluation of a coupling system's ***play*** (e.g. a claw coupling in accordance with ref. H) should take into account not only the system in its new condition but also any changes brought about by prolonged loading (Fig. 8.1.2).

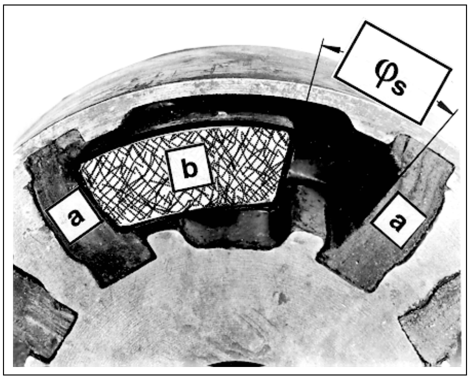


Fig. 8.1.2
Claw coupling after prolonged reversing operation

φ_S Heavily increased rotational play
a Compressed leather package
b Champfered claws

The replaceability of wear elements in clutches is also important: Fig. 8.1.3 shows an example of a type of installation that is particularly easy to service.

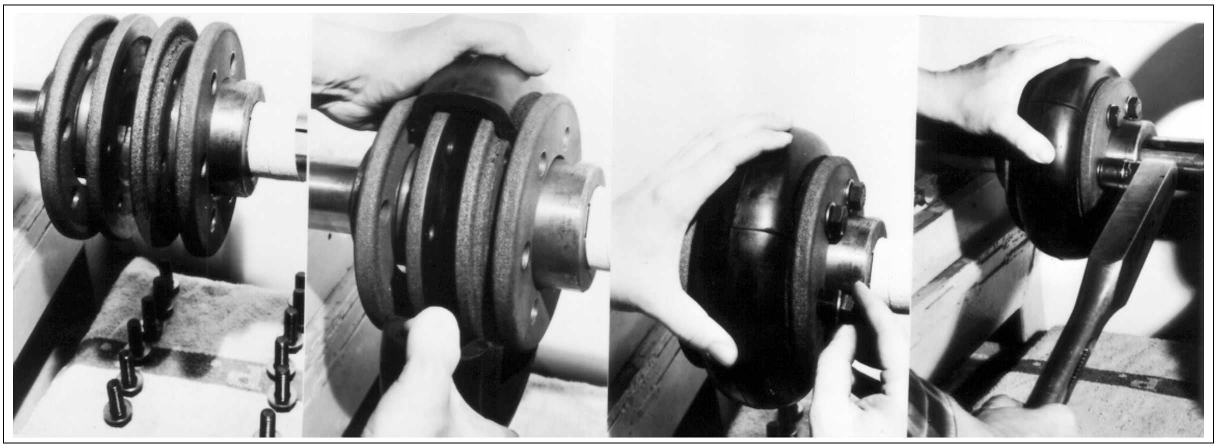


Fig. 8.1.3
Replacement of the resilient shaft tyre on a PERIFLEX coupling (manufactured by STROMAG)

Table 8.1.4 Evaluation of various types of clutch construction

☺ Very suitable
😐 Limited suitability
☹ Not suitable

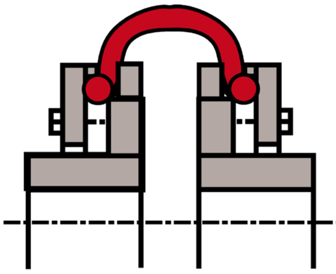
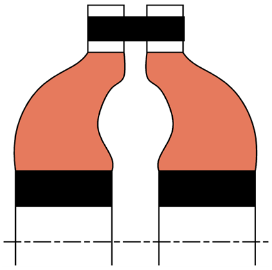
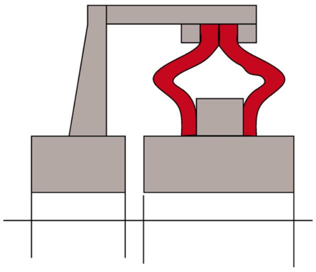
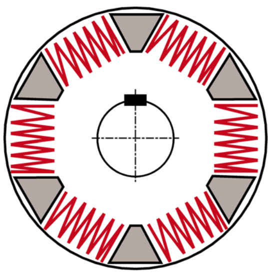
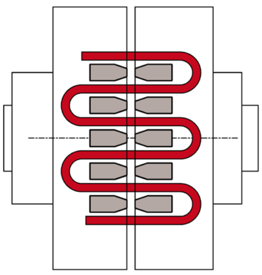
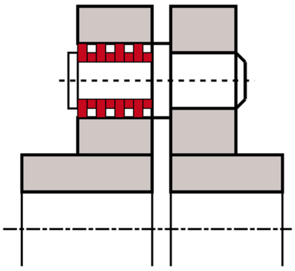
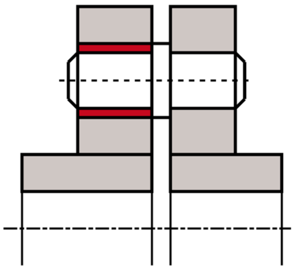
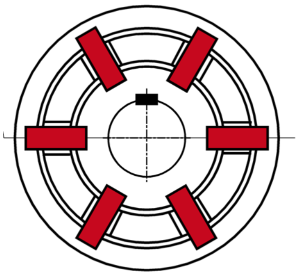
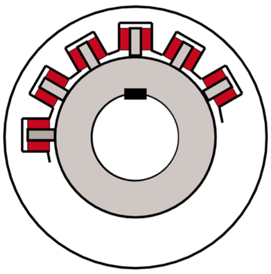
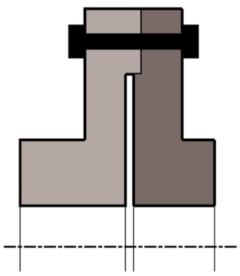
Ref.	System	Evaluation in terms of				
		Freedom from play	Elasticity	Permissible displacement		Suitable for switching operation
				parallel	angular	
A		☺	☺	☺	☺	☺
B		☺	☺	☺	☺	😐
C		☺	☺	☺	☺	☺
D		☺	☺	☺	☺	☺
E		☺	☺	☺	☺	☺

Table 8.1.4 (ctd.)

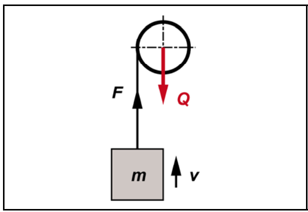
		Evaluation in terms of				
Ref.	System	Free-dom from	Elasticity	Permissible displacement		Suitable for
		play		parallel	angular	switching operation
F		😐	😐	😐	😐	😐
G		😐	☹	😐	😐	☹
H		☹	☹	😐	😐	☹
I		☹	☹	😐	😐	☹
J		☺	☹	☹	☹	☹

8.2 Flexible drives with radial force (overhung load)

8.2.1 Level and direction of the overhung load

The thermal and mechanical rating of the geared motor is designed to transmit its nominal torque M_N under continuous loading conditions. This rated torque is used as a driving force at the external transmission component (e.g. chain sprocket, gear wheel, belt pulley, crank shaft).
The force F can be calculated by using the following formulas:

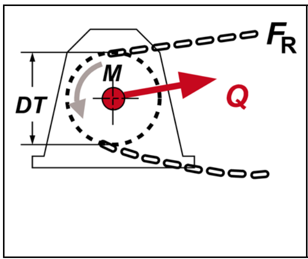
Translation



$$F = \frac{1000 \cdot P}{v}$$

Fig. 8.2.1.1
F - Force (N)
P - Power (kW)
v - Velocity (m/s)
Q - Overhung load on the output shaft (N)

Rotation



$$M = \frac{9550 \cdot P}{n}$$

$$F = \frac{M}{D_T/2} = \frac{19100 \cdot P}{n \cdot D_T}$$

Fig. 8.2.1.2
M - Torque (Nm)
P - Power (kW)
n - Rotational speed (r/min)
F - Force (N)
DT - Pitch circle dia of transmission element (m) (e.g. gear wheel, sprocket)

If ***positive*** (non-slip) transmission elements (such as chains, gear wheels, toothed belts, push rods, eccentric disks, cam plates) are used the reaction on the driving force F acts as an overhung load Q on the output shaft of the geared motor (Fig. 8.2.2).

8.2.2 Chain drive

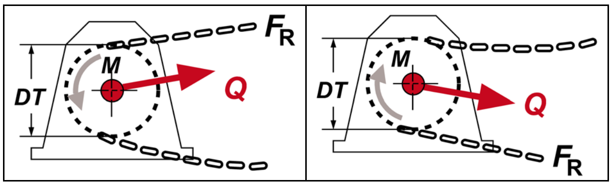


Fig. 8.2.2
Overhung load on the output shaft of a geared motor resulting from a chain drive

The chain pull F acts as an overhung load Q on the output shaft in the direction of the taut side of the chain.

8.2.3 Gear wheel drives

The force on the teeth in cylindrical gear wheels is always at an angle of 20° to the common tangent to the pitch circles of the driving and driven wheels (Fig. 8.2.3). The driving tooth force F (gray arrows) acts on the driven wheel, whereas the driving wheel is loaded by the reaction force (black arrows). The effect of this reaction on the driving shaft can be considered as an overhung load Q acting on it (red arrows).

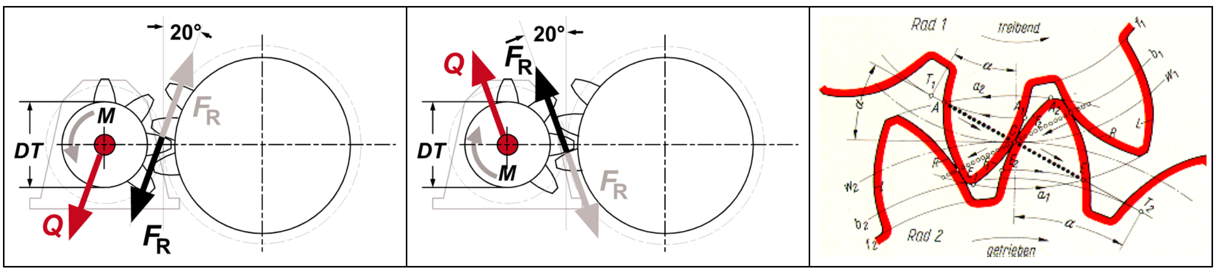


Fig. 8.2.3 Load on the output shaft when driving via cylindrical gear wheels (pressure angle 20°)

8.3 Driving elements with frictional connection

When using transmission elements ***relying on friction***, such as flat belts or V-belts, it is necessary to ***pretension*** them before they can transmit power. In such cases the overhung load on the output shaft consists not only of the usable belt pull but also the initial tension.
The initial tension on the belt should be set just high enough to ensure reliable, slipfree power transmission out of consideration for the belt and bearings. Since belt-tensioning devices often permit easy, but uncontrolled tensioning of belts, it is not uncommon to find belt drives with excessive pretensioning in everyday practice. It is recommended that appropriately large safety factors be used and generously dimensioned output shaft bearings chosen when calculating the resulting shearing forces (Fig. 8.3.1).

8.3.1 Belt drive

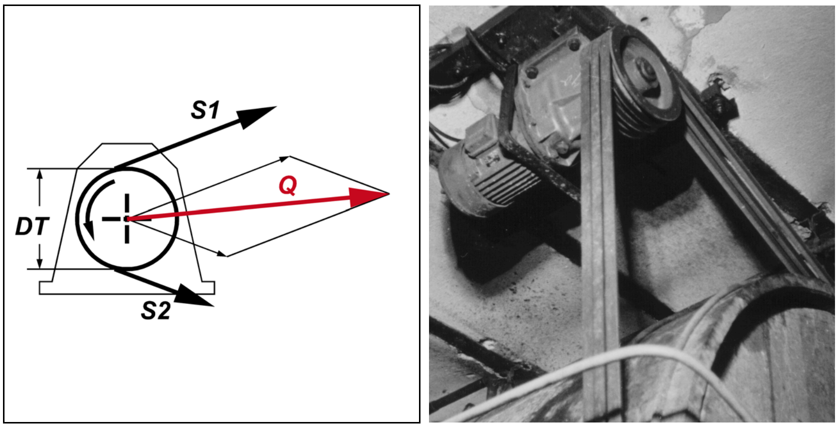


Fig. 8.3.1
Overhung load *Q* on the output shaft resulting from belt forces *S1* and *S2* in a V-belt drive

S1 and S2 are operational belt tensions due to pretension and belt pull *F*.
Q is the overhung force acting on the output shaft between the taut and the slack side of the belt, but tending towards the direction of the former. The following apply, according to the pretension,

- ☐ for belt drives: $Q = (2 \text{ to } 2.5) \cdot F$
- ☐ for flat belts: $Q = (2 \text{ to } 3) \cdot F$

The output shaft bearings must be dimensioned to take the total overhung load Q.

8.3.2 Friction wheel drive

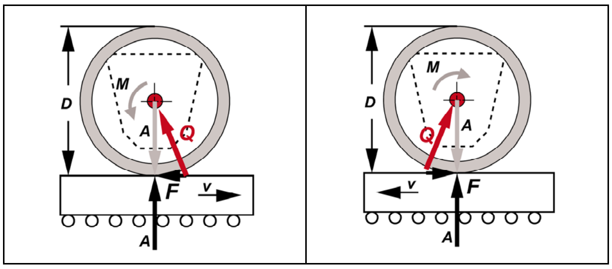


Fig. 8.3.2
Load on the output shaft when driving via friction wheel

In order to transmit the usabel ***tangential force F*** to the conveyed material the friction wheel must be pressed against that material with the ***pressure A*** (Fig. 8.3.2). The contact pressure must be at least

$$A = \frac{F}{\mu}$$

where μ is the coefficient of friction between the friction wheel and the surface of the conveyed material.
The resulting overhung (radial) force is then

$$Q = \sqrt{A^2 + F^2}$$

Under normal conditions encountered in practice
$Q = (3 \ldots 4) \cdot F$.

8.4 Capacity of the output shaft bearings

The total loading on the output shaft bearings of a geared motor is composed of the tooth force generated inside the gearing and the external overhung load on the shaft extension. The permissible radial force id given in the catalogue (both in the printed and CD version). The overhung load can be excessively high without exceeding power or torque if the pitch circle diameter is too small or if the transmission component is located at too great a distance from the shaft collar.

8.4.1 Guide values for the permissible rated radial force

Guide values from Fig. 8.4.1 may be used in case the manufacturers documentation is not available. The figures are related to a point of application at half of the shaft extension and to output speeds up to 20 r/min (see also 8.4.2 and 8.4.3).

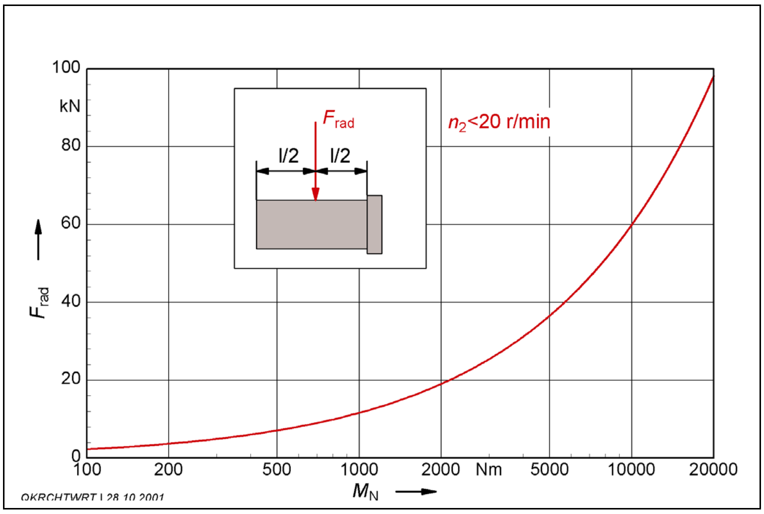


Fig. 8.4.1
Guide values for the permissible radial force on the output shaft og high quality geared motors

Effects of speed and actual distance from the shaft collar need to be considered

8.4.2 Effect of the output shaft speed

Guide values to Fig. 8.4.1 are related to strength of the shaft and gear box; the can be used for low speeds. In case of higher output speeds n_2 > 20 r/min a reduction factor (Fig. 8.4.2) must be applied because of the life of the rolling bearings.

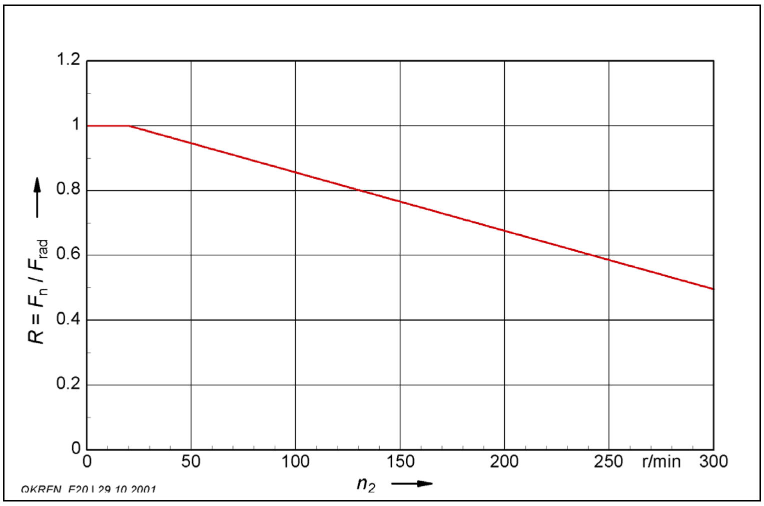


Fig. 8.4.2
Reduction factor R for permissible nominal overhung loads depending on output speed n_2

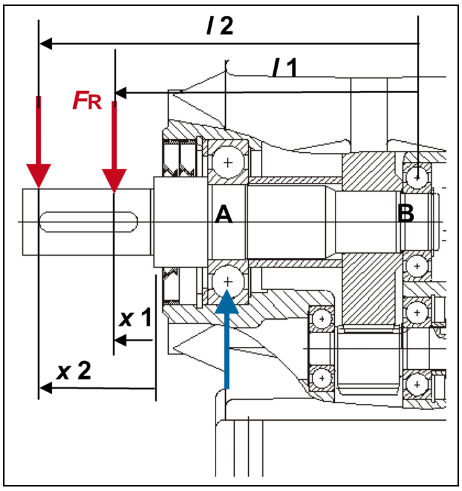
F_n - Radial force at speed n_2
F_{rad} - Radial force at speed 20 r/min (max. value related to tensile strength of shaft and gear housing)

8.4.3 Application of force on the shaft extension

The bending moment on the output shaft and consequently the stresses on the shaft and bearings is not only dependent on the magnitude of the shearing force but also on its point of application in the axial direction.

Fig. 8.4.3.1
Example for the arrangement of the output shaft bearings of a geared motor and for the effect of the distance x1 or x2 on the actual load of the outer bearing »A«

Design: Danfoss Bauer GmbH



The “long series” of the standardised shaft end lengths in accordance with ISO 775 permits the transmission of the ascribed nominal torque, even with belt drives, which require wide pulleys (= long shaft extensions). For transmission elements with positive engagement (chain or gear wheels, for example), the “long shaft” is unnecessarily long and leads to an unfavourable location of the force application point and, because of the long lever arm, loads the first bearing unnecessarily.
The smaller the distance *x* selected from the shaft support point, the greater the shearing force F_x may be, given the same calculated service life of the rolling contact bearings and compliance with the permissible bending load on the output shaft (Fig.8.4.3.2). The size and arrangement of the power transmission component (e.g. a chainwheel) may have a decisive effect on the service life (Fig.8.4.3.3).

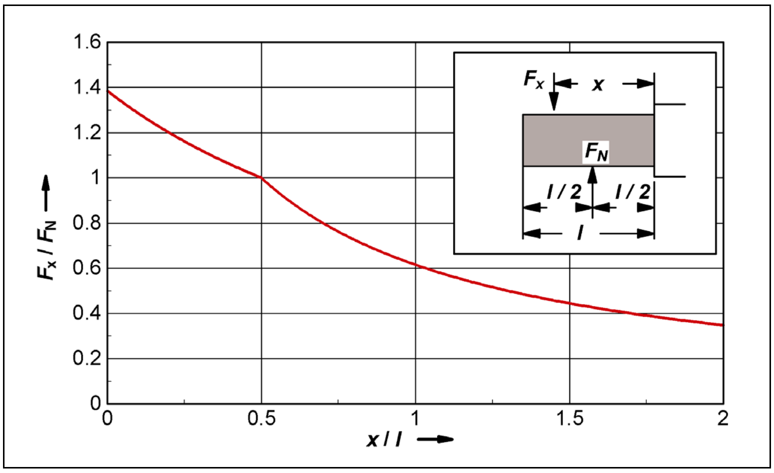


Fig. 8.4.3.2
Change of the permissible shearing force F_x against the normal value F_N if the distance from the shaft collar *x* is altered against the normal value *l* / 2

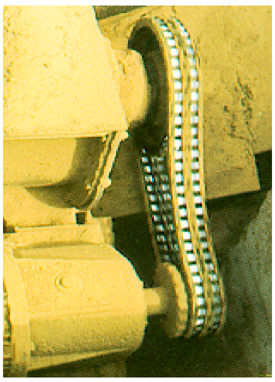


Fig. 8.4.3.3
Frequently used but unfavourable arrangement of a sprocket at the end of an output shaft extension

8.5 Polygon effect

The chain lies in the form of a polygon on the chainwheel; hence, the effective pitch circle diameter and the chain speed will vary in the ratio of 1: cos α, where α is half the angle between adjacent teeth on the chainwheel ($\alpha = 180/Z$) – see Fig. 8.5.1.

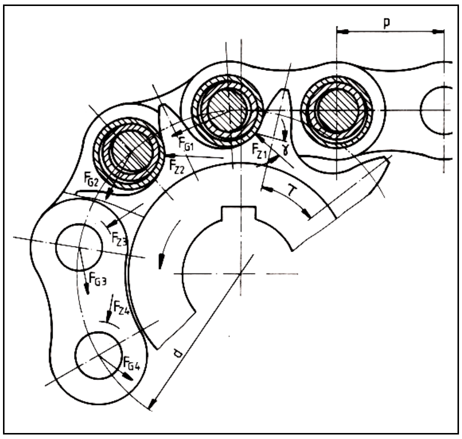


Fig. 8.5.1
Geometric arrangement of a chain sprocket to explain the polygon effect

Source: Arnold und Stolzenberg

This ***polygon effect*** becomes more pronounced as the number of sprocket teeth *Z* is reduced. This and other reasons is why DIN 8195, "Selection of chain drives" recommends that chainwheels with at least 17 teeth be chosen. The chainwheel manufacturer will certainly normally support this recommendation but may offer drives with as few as 10 or 11 teeth on the chainwheel. Figures 8.5.2 and 8.5.3 show the polygon effect, i.e. the ***irregularity*** of the chain speed in relation to the number of teeth on the sprocket.

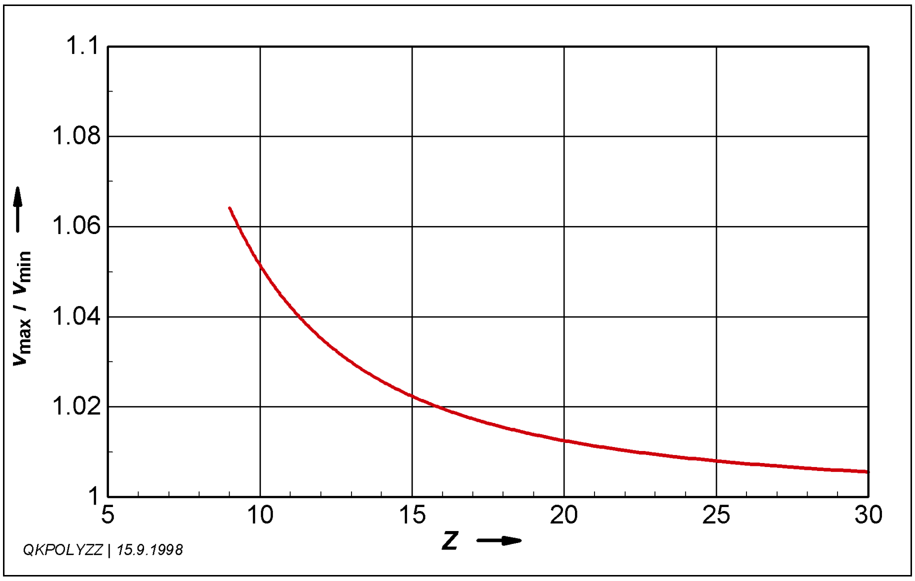


Fig. 8.5.2
Polygon effect causing irregularity of the chain speed v_{max} / v_{min} in relation to the number of teeth *Z* on the sprocket

In extreme cases, the irregularity of speed may amount to about 5 %. This would be troublesome in many drive applications but is often unimportant. However, the polygon effect also has a dynamic influence due to the occurrence of dynamic forces leading to excessive increase in the radial loading of the output shaft depending on the absolute value of the chain speed and the masses concerned. Figures for this polygon are difficult to calculate since the peak values, which are theoretically very high, are more or less strongly damped by the elasticity of the chain. The following information on the minimum pitch circle diameter of chainwheels and the catalogue data on the permissible radial forces of the individual drives therefore applies for normal conditions, namely :

- ☐ for the number of pinion teeth recommended in DIN 8195 (*Z* = at least 17),
- ☐ for low chain speeds (up to about 0.5 m/s),
- ☐ for normal factors of inertia (*FI* up to about 1.5).

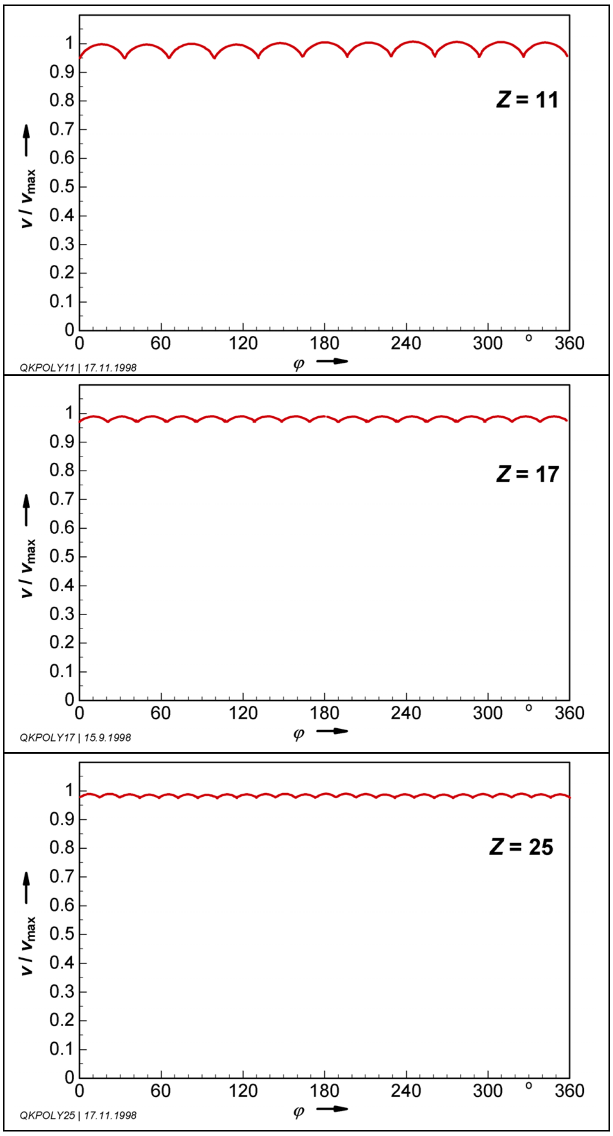


Fig. 8.5.3
Polygon effect causing irregularity of the chain speed v / v_{max} in relation to the angle φ of the output shaft for chainwheels with a number of teeth
Z = 11 / 17 / 25

8.6 Sense of rotation and direction of force

The force F_{RE} (Fig. 8.6.1) is acting in the tooth engagement of the final stage; its direction depends on the arrangement of pinion and wheel and on the direction of rotation. The level is given by the torque. The external force F_{RA} acting on the output shaft depends on the specific application; it can take any direction on the circumference of the shaft.

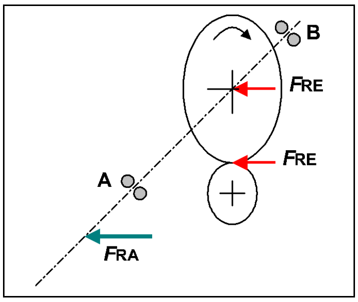
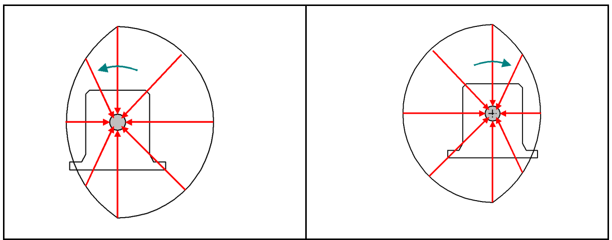


Fig. 8.6.1
Direction of the internal tooth force F_{RE} depending on the sense of rotation;
Direction of the external usable force F_{RA} is optional

The effect of the two forces on the mainly stressed outer bearing »A« can be badly added or partly compensated. For a certain bearing fife Fig. 8.6.2 indicates a scheme of the permissible forces depending on sense of rotation and direction of force application.



ccw rotation	cw rotation

Fig. 8.6.2
Scheme of external radial forces depending on the sense of rotation and direction of force application related to a certain bearing life under any of these conditions

A combination of both diagrams indicates in Fig. 8.6.3 that for a simple statement in the catalogue or in other selection data sheets there is only the possibility to give the lowest permissible radial force F_{RN} (CAT) related to the unfavourable direction as the general limit and to make no use of the higher values permissible in the other directions. For the user Fig. 8.6.3 also indicates that forces acting at rightangles to the feet face – standard arrangement for the internal gear provided – would allow higher forces or provide longer nominal life than directions parallel to the foot face.
Some manufacturers use a diagram similar to Fig. 8.6.4 with a factor f_α by which the nominal radial force can be increased as a function of its direction of application on the circumference of the output shaft.

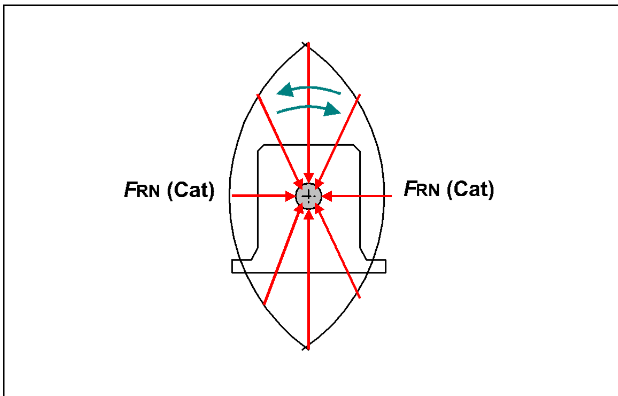


Fig. 8.6.3
Simple catalogue statement F_{RN} for the smallest permissible radial force – thus allowing a safety margin at right angles to the feet face

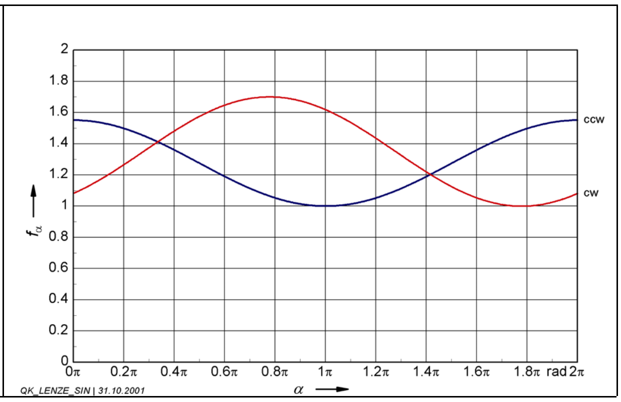


Bild 8.6.4
Factor $f\alpha$ for the direction of application allowing an increased force on the output shaft
cw = clockwise ccw = counter clockwise
Source: LENZE

8.7 Excessive overhung loads are not indicated by current reading

Most motor protection devices (current-dependent thermal overload relays or direct temperature monitoring thermistors) are based on the direct or indirect thermal effect of the current. Therefore they cannot detect any mechanical overload on the output shaft and its bearings which is caused by wrong planning. the following practical example is to explain why secondary current-related protective measures can not be effective:
a simple hoisting arrangement is normally used under conditions as stated in the left column of Fig. 8.7.1. In a special case double the load shall be lifted. The planning engineer has a good idea: The outer diameter of the rope pulley is machined at 50 % keeping all other conditions constant. After measuring the same current (same power output) everything seems to be all right.

Looking at the right column the bearings of the geared motor output shaft are overloaded, however.

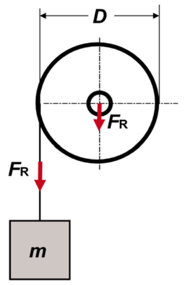
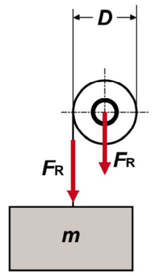
	
D = 100 mm m = 200 kg $F = m{\cdot}g = 200{\cdot}9{,}81 \approx 2000$ N $M = F{\cdot}D/2 = 2000{\cdot}0{,}05 = 100$ Nm n_2 = 105 r/min $v = \frac{\pi \cdot D \cdot n}{60} = \frac{\pi \cdot 0{,}1 \cdot 105}{60} = 0{,}55$ m/s $P = \frac{M \cdot n}{9550} = \frac{100 \cdot 105}{9550} = 1{,}1$ kW I_N = 2,7 A F_{RN} for gear unit acc. to catalogue: 3150 N Relative load : 2000 / 3150 = 63 %	D = 50 mm m = 400 kg $F = m{\cdot}g = 400{\cdot}9{,}81 \approx 4000$ N $M = F{\cdot}D/2 = 4000{\cdot}0{,}025 = 100$ Nm n_2 = 105 r/min $v = \frac{\pi \cdot D \cdot n}{60} = \frac{\pi \cdot 0{,}05 \cdot 105}{60} = 0{,}275$ m/s $P = \frac{M \cdot n}{9550} = \frac{100 \cdot 105}{9550} = 1{,}1$ kW I_N = 2,7 A F_{RN} for gear unit acc. to catalogue: 3150 N Relative load: 4000 / 3150 = 126 %

Fig. 8.7.1 Example of calculation the overloading by overhung load on the output shaft without indication via current reading

Fig. 8.7.2
Example for a V-belt drive with high overhung loads on the geared motor output shaft used to drive drums in a tannery

8.8 Fitting the power transmission components

A drive's output shaft is usually ground to ISO k6 or m6. The catalogue data or the relevant dimension drawing is decisive in case of doubt. The power transmission component's bore must be measured to ISO H7 to ensure correct seating; the tolerances may be found in the operating instructions.
Power transmission components must be fitted carefully and gently onto the shaft, preferably using the tapped end hole provided for this purpose in the end face of the shaft in accordance with DIN 332 (Figures 8.8.1 and 8.8.2). Heating the power transmission components being fitted to about 100 °C makes the task easier and protects the components.

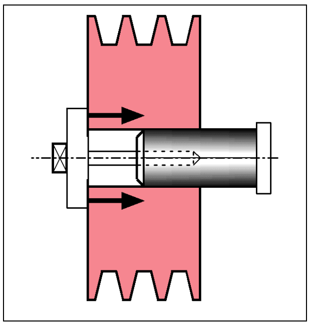
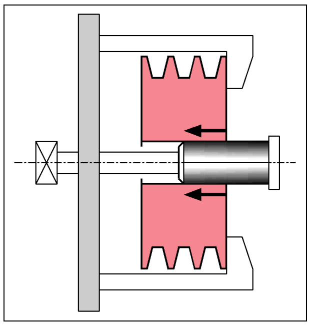


Fig. 8.8.1
Fitting a power transmission component on the output shaft using the tapped end hole

Fig. 8.8.2
Removing a power transmission component using a commercial puller



Provided the shaft being driven has been prepared according to the manufacturer's specifications in the relevant catalogues, fitting and removing a gear unit with a hollow shaft should present no problems either (Fig. 8.8.3).

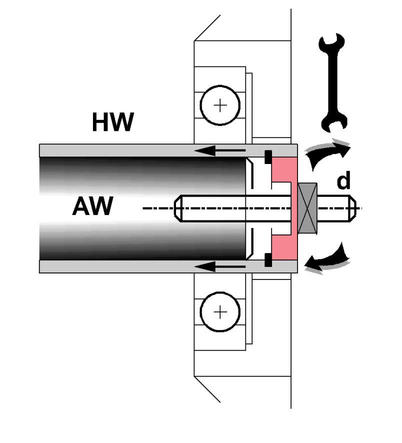
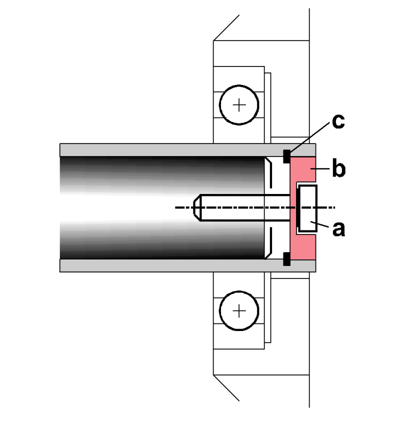
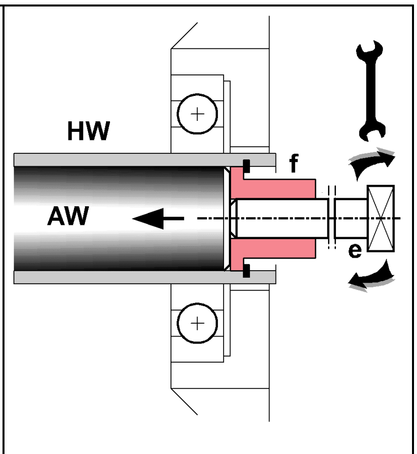
		
Fitting A threaded bolt (d) is screwed into the end thread of the shaft to be driven (AW). The hollow shaft (HW) of the slip-on gear unit is pressed onto the shaft over the pressure piece (b) and retaining ring (c) with the aid of the nut.	Setting axially The pressure piece (b) is rotated and fitted against the retaining ring (c) using the socket head cap screw (a). The hollow shaft and shaft to be driven are set mutually.	Removing An extractor (f) is fitted between end face of the shaft and the retainer ring (c). The jack screw (e) pushes against the end face of the shaft of the shaft to be driven (AW) and removes the slip-on gear unit's hollow shaft (HW).

Fig. 8.8.3 Fitting aid for slip-on shaft-mounted gear units

8.9 Balancing motors and fitting elements

This section explains the background to the new standard, compares the new regulations which widespread in the past but are now mandatory for all manufacturers, and provides information on the correct assembly of “fitting elements” (couplings, belt pulleys, flywheels) on the shafts of standard motors.
The subject of “half-key balancing” is discussed in full in [3.10].

8.9.1 Standard key conventions

The balancing method must be agreed where shafts or rotors with keys (for example on rotating electrical machinery) and the fitting elements to be fitted onto them are manufactured separately and only assembled at the installation location. The following conventions are currently recognized:

- full-key convention (“full-key balancing”)
- half-key convention (“half-key balancing”)
- no-key convention (“balancing without a key”)

8.9.2 New international conventions

The half-key convention was introduced in 1989 with ISO 8821 and adopted as a German standard as DIN ISO 8821 in 1991. 1990 has been set as the year in which this standard will be introduced and become applicable to all machines of this type. A CENELEC harmonisation document (HD) on full-key balancing has been in force since 1978 for rotating electrical machinery; this was superseded by a new HD on half-key balancing in 1992. This specified 01.06.1998 as the end of the transitional period for the manufacture of electrical machinery with full-key balancing.
The general ISO requirement has been formally implemented with EN 60034-14 / IEC 60034-14 [1.14] for rotating electrical machinery.

8.9.3 Marking and supply convention

The use of half-key balancing must be permanently marked near the keyway by the *letter “H”* – on the end face of the shaft end in the case of motors and on the end face visible after assembly in the case of fitting elements. Punches, ultrasonic engraving machines and indelible inks are permitted by the standard. If the end face of the shaft is too small, the standard specifies the keyway ground as an alternative (highly unsuitable from a practical point of view). The standards committee views a marking on the rating plate as entirely appropriate.
The use of ***full-key balancing*** was not previously been marked; this practice may continue upon agreement between the customer and the manufacturer. This balancing method is marked by the letter “F” (full-key convention) where necessary.
Half-key balancing should have been the standard design for manufacturers of motors and fitting elements since 01.06.1998. ***All special designs which deviate from this must be agreed***.

8.9.4 Possible assembly faults

Many possible assembly faults will arise from the new balancing convention, particularly during the introductory period. Three likely faults are described:

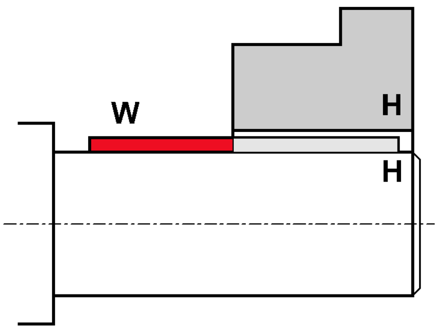


Fig. 8.9.4.1
Potential fault: Shaft with half-key balancing
Hub with half-key balancing.
Excess length of key generates out of balance W.

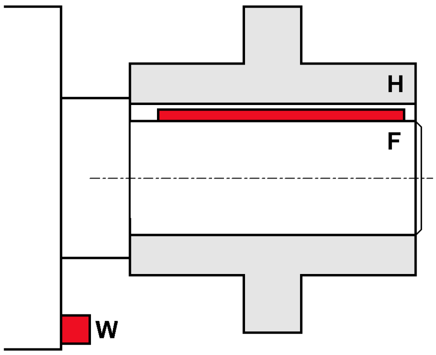


Fig. 8.9.4.2
Potential fault: Shaft with full-key balancing
Hub with half-key balancing
Key diameter overshoot is balanced on the laminated core by additional weight “W” in relation to the rotor.
The balance weight W would be unnecessary for a motor employing the “H” balancing method – this combination would cause an imbalance.

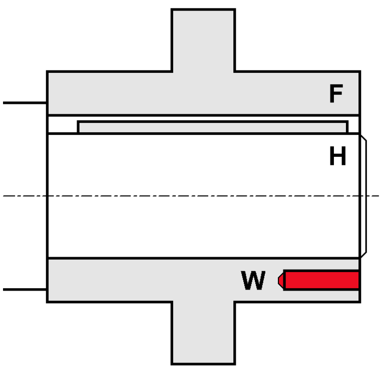


Fig. 8.9.4.3
Potential fault: Shaft with half-key balancing
Hub with full-key balancing.
A lack of balancing bore mass W in the hub would be unnecessary if method “H” is used for the fitting element – this combination would cause an imbalance.

9 Lubrication of the rolling contact bearings

The lubricant – generally grease for standard motors – is intended to prevent metallic contact between the rolling elements, raceways and cage, and thus reduce wear. The lubricant also provides corrosion protection for these parts. The optimum operating temperature is achieved by supplying the bearings with precisely the quantity of lubricant to provide satisfactory lubrication. Fast-running over-lubricated bearings heat up unnecessarily – the grease ages and loses its lubricating properties.
The grease should also provide a seal against foreign particles and moisture – the bearings and enclosure should therefore be completely filled with grease when the machine is rotating at low speed (e.g. at the output shaft on geared motors).

9.1 Lubricant grade

A lithium saponified grease with a mineral base oil in accordance with DIN 51825 is most commonly used for the initial greasing of the rolling contact bearing in the range of standard motor frame sizes. A consistence of NLGI Class 2 or 3 is selected under normal conditions. A grease of this type is designated K-2K or K-3K in accordance with DIN 51502. Special greases are used for particular operating conditions, such as extremely low or high ambient temperatures; these will then be indicated by a special label or plate on the motor.
The different ***ranges of penetration*** have been classified by the NLGI (National Lubricating Grease Institute) and DIN 51818 into ***consistence classes*** as shown in Table 9.1. The scope of the standard does not include a description of the condition.

Table 9.1 Classification of greases into consistence classes in accordance with NLGI

NLGI consistence class	Penetration	Description
000	445 to 475	nearly liquid
00	400 to 430	semi-liquid
0	355 to 385	plastic
1	310 to 340	very soft
2	265 to 295	soft
3	220 to 250	semi-firm
4	175 to 205	almost hard
5	130 to 160	hard
6	85 to 115	especially hard

Usual classes for the lubrication of the rolling contact bearings: 2 and 3

9.2 Relubrication interval

9.2.1 Relubrication intervals as specified by bearing manufacturers

Greasing devices for the motor bearings, such as lubrication nipples and grease quantity regulators, are usually only provided on larger units. In the small and medium output ranges, the initial filling is adequate for a relatively long running period. This relubrication interval is dependent on the bearing diameter, the type of bearing race, the speed, the temperature, the load and the level of pollution.
Some of these influences are difficult to assess and furthermore, the end of the effective life of the lubricant cannot be defined simply. Consequently, the recommended relubrication intervals for rolling contact bearings may be found to vary quite widely.

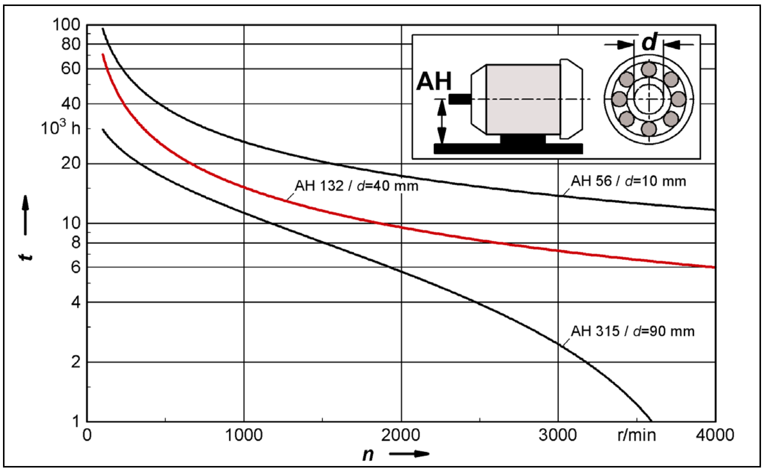


Fig. 9.2.1.1
Relubrication intervals for series 62 rolling contact bearings as a function of boring dia d of the bearing, the motor shaft height *AH* and the speed of rotation *n* as recommended by the firm SKF in their main catalogue

Fig. 9.2.1.1 translates the recommendations of a rolling contact bearing manufacturer onto the range of standard motor. The relubrication intervals suggested here are surprisingly low compared to general experience and also to other publications of this manufacturer and are therefore on the safe side. The diagram has been reduced to three shaft heights (AH) to highlight the major ***influence of the speed*** noticeable mainly on large frame sizes (AH = 315 in the example).
The same rolling contact bearing manufacturer's newsletter reports on a long-term trial under defined operating conditions where far longer relubrication intervals were permitted. Favourable ambient conditions are a prerequisite of these maintenance intervals, which must currently be viewed as the upper limit. These comprise mainly the avoidance of dirt and water and a relatively low operating temperature below about 50 °C.
If one applies these recommendations to the industry-standard 4-pole three-phase asynchronous motor running at 1500 r/min, this gives the scatter band shown in Fig. 9.2.1.2 for the relubrication interval *t* (in years) plotted against the nominal output P_N. There is a span of 1 : 3 to 1 : 5 between the upper and lower limits; this shows that the intervals at which rolling contact bearings should be relubricated cannot be specified as an absolute value but that they are very dependent on the operating conditions. Whether one should tend towards the upper or the lower limit will also depend on the level of reliability required of the apparatus or installation concerned.

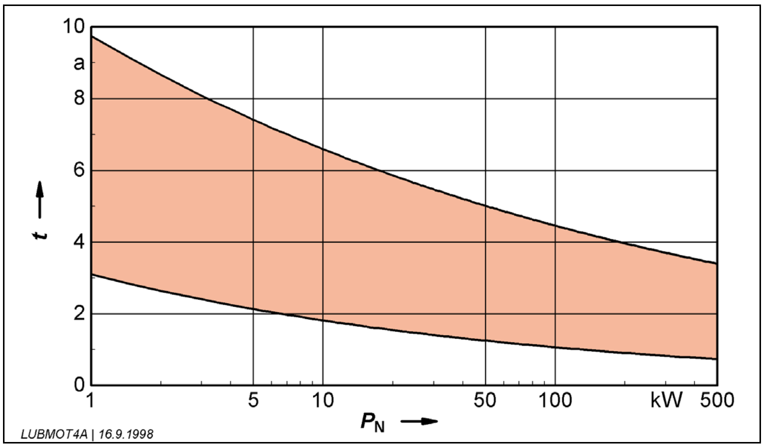


Fig. 9.2.1.2
Rolling contact bearing relubrication interval *t* (in years) for 4-pole three-phase cage motors as a function of the rated output P_N

9.2.2 Relubrication interval as specified by the VIK

VIK, the “Verband der Industriellen Energie- und Kraftwirtschaft e.V.” [German Association of Industrial Producers of Electricity] has drawn up “Technical requirements on three-phase asynchronous motors” which serve as guidelines for many users in the chemical and raw materials industries and are also of interest in this context:

"Bearings must be provided with lifetime lubrication with a pot life of at least 20,000 operating hours for 4-pole and multipole motors and at least 10,000 operating hour for 2-pole motors at a coolant temperature of 40 °C.

For a 15 K fall in the coolant temperature, a pot life of approximately 40,000 operating hours for 4-pole and multipole motors and approximately 20,000 operating hour for 2-pole motors may be expected.

Motors above a shaft height of 250 may be fitted with relubrication devices with lubricant quantity regulators. The relubrication interval should be 5000 operating hours if possible, but more than 4000 operating hours, for 4-pole and multipole motors and at least 2500 operating hours, but more than 2000 operating hours, for 2-pole motors at a coolant temperature of 40 °C.

For a 15 K fall in the coolant temperature, a relubrication interval of approximately 10,000 or 8000 operating hours may be expected for 4-pole and multipole motors and approximately 5000 or 4000 operating hours may be expected for 2-pole motors."

This also highlights the marked influence of the operating temperature, as is the case with winding insulation ageing.

9.2.3 Relubrication interval according to the draft for duty type S1

There is a draft of supplement 1 with the short name “duty type S1” to DIN VDE 0530 titled “Guidelines on the installation and operating conditions of general-purpose low voltage cage induction motors with ball bearings or roller bearings under duty type S1 at outputs of up to 315 kW”. This states the following on the topic of "relubrication interval": If the manufacturer’s information is not available, the maintenance interval shall be no more than 2.5 years in the case of outdoor installation or nor more than 4 years in the case of indoor installation. This specification is provided for the purpose of information only and shall not substantiate any claims against the warranty."

9.3 Temperature range

The lower limit of the permissible temperature range is determined by the requirement for reliable starting. The same low temperatures permitted for a relatively large drive using direct-on-line switching from a stiff system cannot be permitted for extremely “soft” starting on a small motor – e.g. using an electronic soft starter.
The higher the temperature, the faster the lubricant will age. The resulting products of ageing impair the performance of the lubricant. Since ageing is always a product of temperature *and* time, both factors must be taken into account.
SKF recommends an ***operating* temperature** of –30 to +110 °C for the most commonly used lithium saponified greases. Guide values for the ***ambient*** temperature in relation to the bearing heating are given in Fig. 9.3.

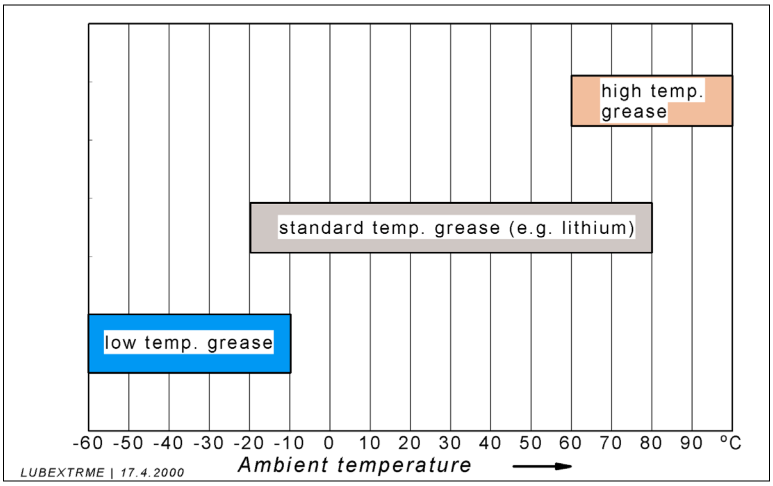


Fig. 9.3
Guide values for the temperature/operating range of conventional and special roller contact bearing lubricants

9.4 Loadbearing capacity

The high degree of development amongst all reputable lubricant manufacturers means that differences between individual brands are only slight.
Fig. 9.4 explains only one of the many tests during the development of a lubricant and which the user may assume to have been carried out.

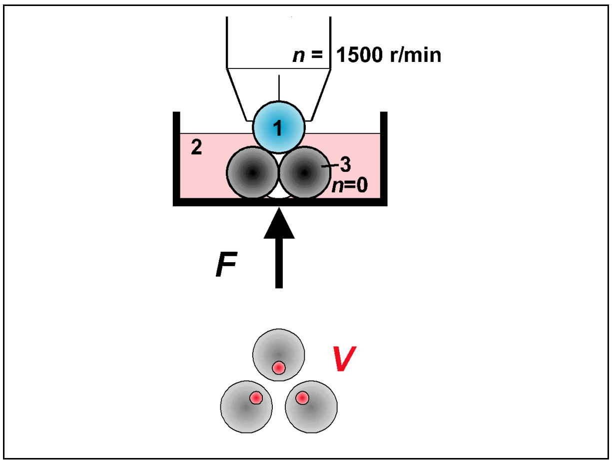


Fig. 9.4
Test of the loadbearing capacity of roller contact bearing lubricants with the SHELL four-ball apparatus (VKA)

1	One rotating ball
2	Test sample (grease)
3	Three stationary balls
F	Load
V	Wear as a measure of the subjective assessment

9.5 Relubrication device

The drive for rationalization, even in the field of maintenance, have led to the call for electrical machinery's rolling contact bearings to be equipped with permanent lubrication wherever possible. However, diagram 9.1 shows that the relubrication intervals to be expected are relatively short for increasing bearing diameters (= shaft heights) and high speeds. Larger machines therefore have relubrication devices (such as the one shown in Fig. 9.5.1) for the rolling contact bearings.

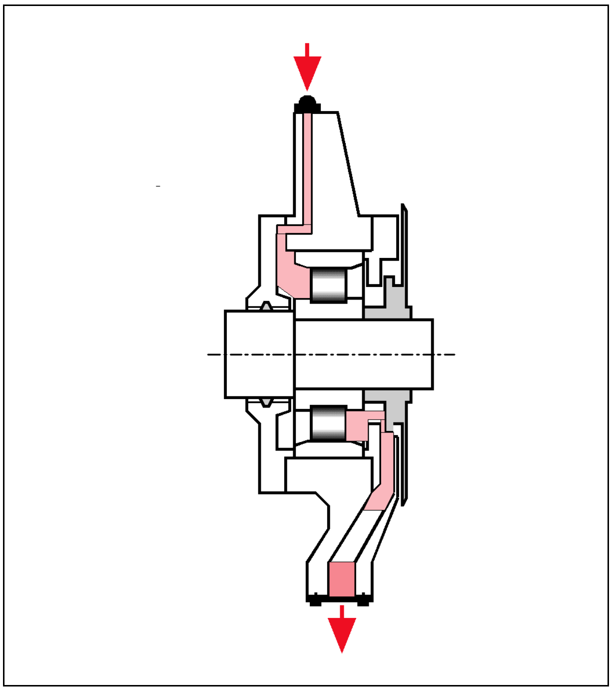


Fig. 9.5.1
Diagram of a relubrication device for rolling contact bearings on electric motors above a shaft height of 200

Source: Danfoss Bauer GmbH

The "Technical requirements on three-phase asynchronous motors" drawn up by the VIK (Verband der Industriellen Energie- und Kraftwirtschaft e.V.) [German Association of Industrial Producers of Electricity] permits relubrication devices for motors above a shaft height of 250. The standard design listed in the catalogues of most manufacturers of standard motor comply with this requirement (Table 9.5.2).

Table 9.5.2 Relubrication device as part of the standard design according to the catalogue data of seven German manufacturers of standard motors

Make	Shaft height (mm)				
	200	225	250	280	315
A	□	□	□	■	■
B	□	□	□	□	■
C	□	□	□	■	■
D	□	□	□	□	■
E	0	0	0	■	■
F	0	□	□	□	■
G	0	0	■	■	■

0 Relubrication device not available
□ Relubrication device is available as special on extra cost
■ Relubrication device is available as standard

9.6 Compatibility

It must be ensured that the grades of lubricant used for bearings which can be relubricated are compatible both in terms of their chemical composition and their lubricating properties, otherwise consistence and lubricating properties may be unforeseeably altered. This applies in particular to greases with synthetic base oils. Table 9.6 is taken from an NLGI (National Lubricating Grease Institute) publication:

Table 9.6 Compatibility of contact roller bearing lubricants (in accordance with NLGI)

Soap base ⇒ ⇓		A	B	C	D	E	F	G	H
Aluminium complex	A	■	0	0	0	0	0	■	0
Barium complex	B	0	■	0	0	0	0	0	0
Calcium	C	0	0	■	0	■	■	■	0
Calcium complex	D	0	0	0	■	0	0	■	■
Lime	E	0	0	■	0	■	0	0	0
Lithium	F	0	0	■	0	0	■	■	0
Lithium complex	G	■	0	■	■	0	■	■	0
Polyurea	H	0	0	0	■	0	0	0	■

0 - incompatible
■ - compatible

10 Gear lubrication

Unlike electric motors, which have been standardized to some extent, there are wide variations in the design, use and construction of reduction gearing. The following general instructions must therefore be supplemented in each case by the specific service regulations for the particular model.

10.1 Penetration of semi-fluid gear greases

The ***flow characteristic*** of a grease is an important prerequisite of the effectiveness of gear lubrication as solid greases (such as roller bearing greases) would be thrown off and form “tunnels”, which would inevitably lead to the gear wheels running dry.
Penetration can be used as a measure of a grease's flow properties. This is determined in accordance with DIN 51804. The point of a test cone is set on the surface of the grease sample and the depth to which the cone penetrates in five seconds is measured and stated in tenths of a millimetre. The penetration number thus represents the ***softness*** of a grease (Table 9.1 and Fig. 10.1.1).

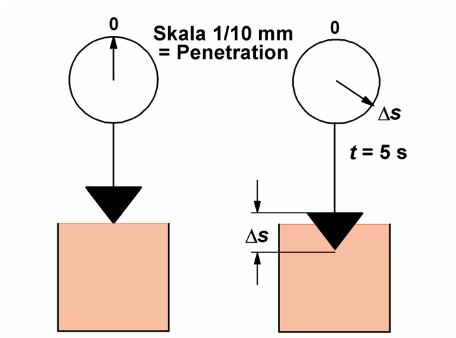
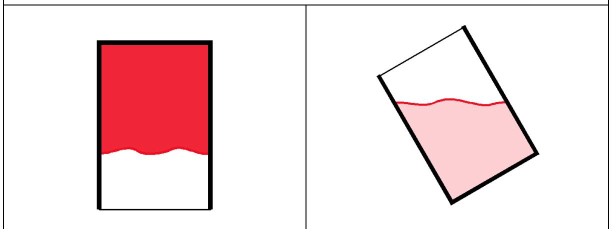


Fig. 10.1.1
Determination of the penetration of a grease using test equipment in accordance with DIN 51804



Rolling bearing grease Penetration 2 to 3	Liquid gear grease Penetration 000 to 00

Fig. 10.1.2
Practical test to differentiate rolling contact bearing grease and liquid gear grease

While penetration class 2 or 3 greases are generally used for lubricating the rolling contact bearings, class 00 or 000 liquid gear greases are used for lubricating the gear unit (Fig. 10.1.2). The penetration class is generally a component of the grade designation and should always be noted as an important basic requirement.
The low demand for liquid gear greases by comparison with gear oils has lead to the quality and availability of liquid gear greases being less highly developed than of oils. Greases are thus now only used for ***small*** reduction gear units and in special cases.

10.2 Viscosity

The viscosity of an oil, together with its viscosity/temperature characteristic (represented by a VT graph) is decisive for start-ups at low ambient temperatures and above all for sealing at high operating temperatures. It is of secondary importance for the ***pressure absorbing capacity*** on low-speed, highly-loaded gear units. Fig. 10.2 compares a few viscosity grades commonly used in practice. Classification into ***ISO viscosity grades*** (ISO VG) has been implemented internationally and is used by mineral oil suppliers. The ***Engler grades*** common in the past have been included in the comparison as these indicate how many times longer than water (1 °E) the oil will take to flow out of a test container and so provide very clear overview.

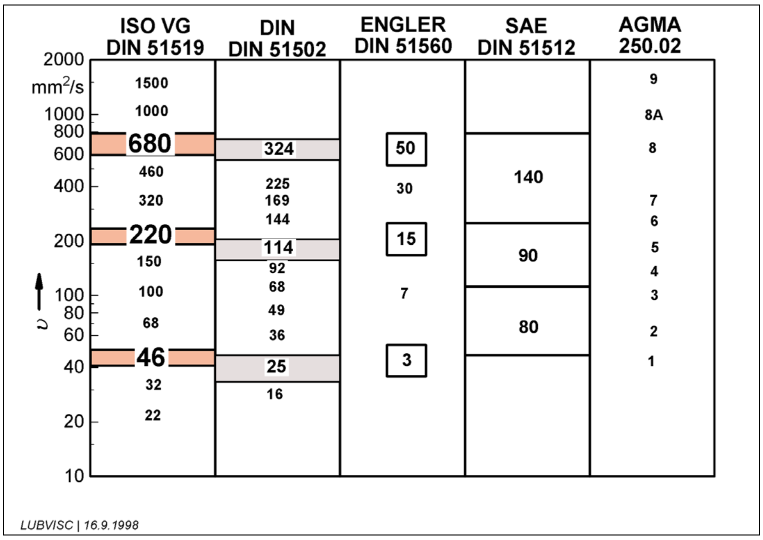


Fig. 10.2
Comparison of viscosity grades common internationally (kinematic viscosity ν at a reference temperature of 40 °C)

The viscosity/temperature characteristic of an oil, that is its increasing viscosity with falling temperature is represented in the VT diagram. The gradient of this line is termed the ***viscosity index (VI).*** Mineral oils generally have a similar tendency, as shown in Fig. 10.6, and even VI improvers cannot significantly alter this. A flatter VT line can be expected with some synthetic oils which is why these more expensive grades are sometimes used where widely fluctuating operating temperatures are encountered (see clause 10.6).

10.3 High-pressure properties of lubricants

With friction bearings, a ***wedge-shaped gap*** filled with lubricant forms between the rapidly-rotating shaft and the bearing shell. Dynamic pressure is generated, the magnitude of which is determined by the slip velocity and the viscosity of the lubricant; the dynamic pressure bears the load (Fig. 10.3.1).
A similar process occurs between two tooth flanks. The ***hydrodynamic share of load bearing*** is dependent to some extent on the viscosity of the oil and to a decisive extent on the (rotational) speed. Fig. 10.3.2 shows that this hydrodynamic effect contributes only slightly to the load-carrying capacity of the lubricant in the speed range of geared motors marked.

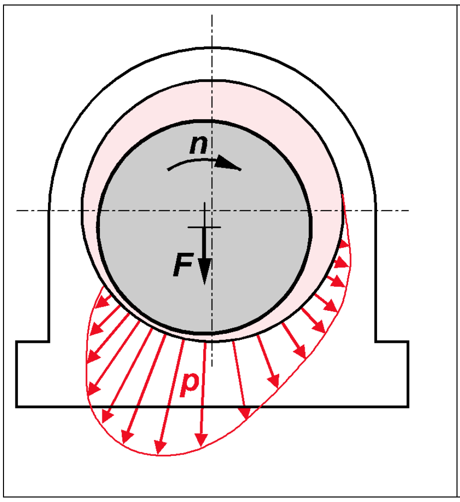


Fig. 10.3.1
Principle of the formation of the a (elasto-)hydrodynamic pressure *p* in a friction bearing

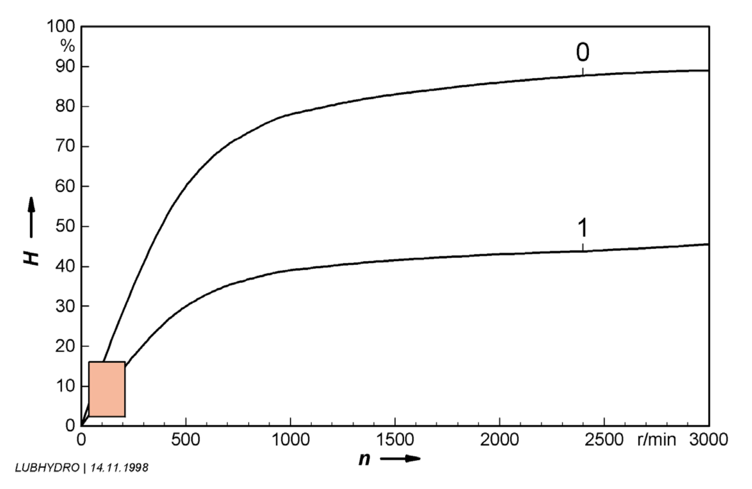
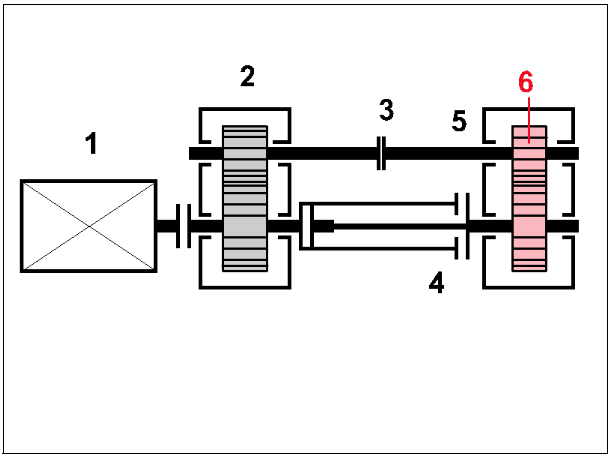


Fig. 10.3.2
Function of the hydrodynamic share of load bearing *H* between tooth flanks at different speeds *n* and loads (0 to 1). The range marked corresponds to the main area of application of geared motors (according to *Bartz*: Getriebeschmierung [Gear lubrication]).

Because a hydrodynamic lubricant wedge is not formed between the tooth flanks in the low-speed stages of reduction gearing, chemical additives are used in modern high-performance lubricants to build up a boundary layer on the gear tooth surfaces and thus prevent metal-to-metal contact under high tooth loads. The oil is “doped”. The effectiveness of these ***high-pressure additives*** or ***EP additives*** (EP = extreme pressure) can be ascertained by a variety of test procedures. The results obtained from the FZG gear wheel torsion test as standardized in DIN 51354 are the most applicable to actual practice (FZG = Forschungsstelle für Zahnräder und Getriebebau [Gear Research Centre, part of the faculty of Machine Engineering at the Technical University Munich).
The principle of the FZG test is shown in Fig. 10.3.3. Specified test gears immersed in the lubricant to be tested run in a test gearbox at a constant speed and defined starting temperature. The gears are subjected to loading increasing in 12 stages by means of a torsion coupling. The loss of weight of the gear wheels due to wear is determined after each load stage and the appearance of the tooth flank damage is described (Fig. 10.3.4).
High-quality lubricants come through the test as far as stage 12 without reaching high-level wear (Fig. 10.3.5).



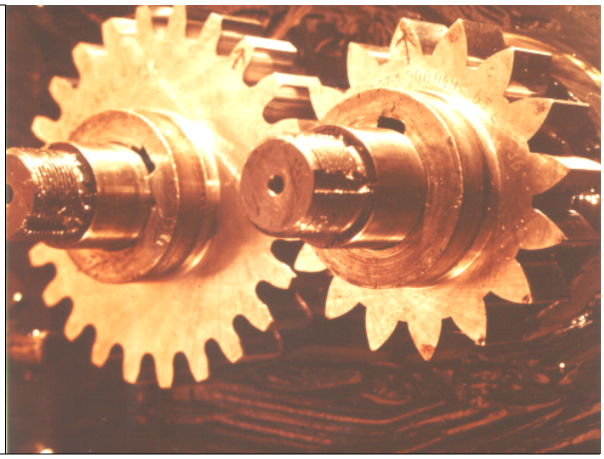


Fig 10.3.3
Principle of the FZG gear wheel torsion test for lubricants in accordance with DIN 51354

1 Electric motor
2 Transmission gear unit
3 Torsion coupling
4 Torque indicator
5 Test gear unit
6 Test gear wheels

Fig. 10.3.4
Test gear wheels in the FZG test rig for testing the high-pressure properties of lubricants in extreme conditions due to poor tooth form

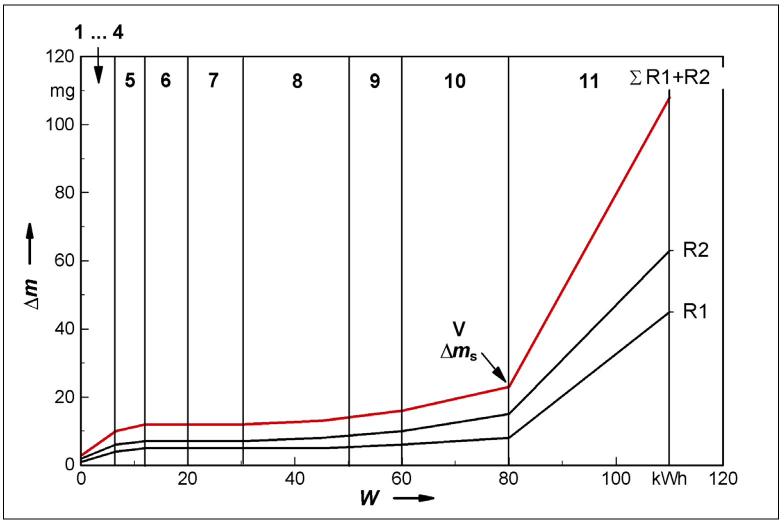


Fig. 10.3.5
Wear Δm on the test gear wheels (pinion R1 and gear wheel R2) after passing through load stages (1 to 11) with transition to high-level wear (grooving or scuffing) at point V (load stage 10) as a function of the overall work transferred W

These minimum requirements on the properties of lubricants for the second filling are described in DIN 51517-3 for CLP lubricating oils or may be found in the gear unit manufacturer's operating instructions (usually in the form of concrete grade specifications).

Since experience has shown that these documents are not available in the workshop at the critical moment, it is recommended that an information plate be mounted on the gear unit (Figures 10.3.6 and 10.3.7).

Fig. 10.3.6
Example of a formerly used information plate lubricant changes with internationally understandable abbreviations

Fig. 10.3.7
Example of currently used information on the main plate with internationally understandable abbreviations

10.4 Ageing resistance of lubricants

The properties of a lubricant change under the influence of temperature and time – it ages. A lubricant with high resistance to chemical change or thermal degradation, that is to say with slow decline in the original properties, is therefore to be recommended, above all for drives where regular servicing is out of the question due to inaccessibility.
If the ***service life*** of a lubricant is defined as the pot life until the load-carrying properties and other characteristic data fall below minimum values, then the rule of thumb applies which states that the service life roughly ***halves*** with an increase in the operating temperature by approximately 10 K. This rule is particularly important where drives are operated at high ambient temperatures (above approximately 30 °C). In these cases, it is recommended that the service period be strictly adhered to or shortened, particularly if the drive is permanently under full load.

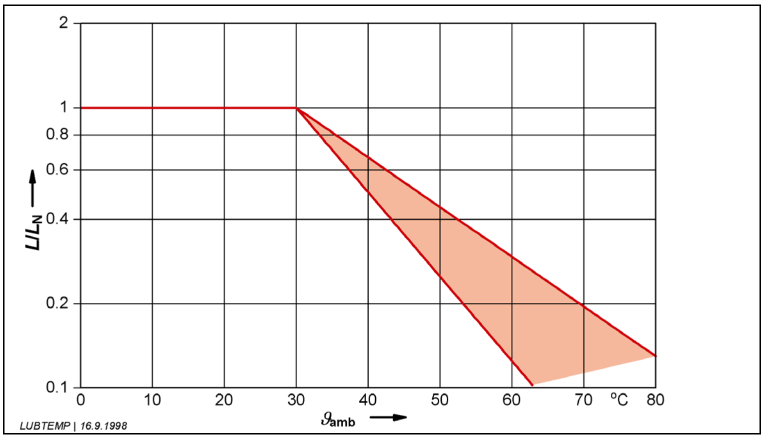
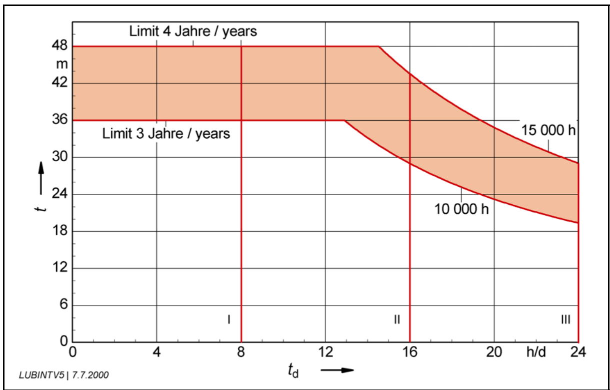


Fig. 10.4
Relative service life L/L_N of a lubricant at various ambient temperatures ϑ_{amb}

The theoretical relationship between temperature and the service life of a lubricant as shown in Fig. 10.4 can, of course, only illustrate a tendency; practical service limits can ultimately only be established in relation to the particular operating conditions of the drive and by experience and testing.

10.5 Relubrication interval

The previous section highlighted the strong influence of the operating temperature on the service life of a mineral oil. Global specification of the correct relubrication intervals is therefore highly problematic. As a practical rule of thumb, a relubrication interval of about 10 to 15,000 operating hours or a maximum time of about 3 to 4 years has been found satisfactory. To the user, this relatively long interval seems reasonable, particularly if one compares it with the normal frequency of oil changes for a motor vehicle gearbox. At an average speed of 50 km/h, the normal service interval of 50,000 km would correspond to an operating time of only 1000 hours.
It would seem appropriate at this point to compare the relubrication interval of 10 to 15,000 hours or 3 to 4 years to actual running times found in practice (Fig. 10.5.1).
For a standard 5-day week (5 d/w), a daily running time of up to roughly 13 hours (13 h/d) is permissible without causing a reduction in the limit value of 3 years = 36 months (36 m). It is only when the average daily utilization exceeds 12 h/d that the 10,000 hour limit would come into play and cause the interval between oil changes to be reduced.
The limit values are reduced accordingly for a 7-day week (7 d/w) (Fig. 10.5.2).



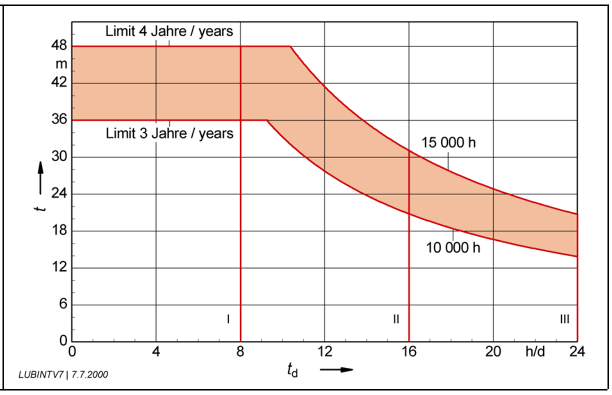


Fig. 10.5.1
5 days per week

Fig. 10.5.2
7 days per week

Time t (in months) for the expiry of a relubrication interval of 10 to 15 000 hours or 3 to 4 years plotted against various operating periods t_d in hours per day (h/d) and days per week (d/w)

5 days per week

Example	Shifts per day	Hours per day	Interval (month)
I	1	8	36 ... 48
II	2	16	29 ... 43
III	3	24	19 ... 29

7 days per week

Example	Shifts per day	Hours per day	Interval (month)
I	1	8	36 ... 48
II	2	16	21 ... 31
III	3	24	14 ... 21

The diagram shows that the ***relubrication interval of 3 to 4 years*** can be adopted for the majority of running times encountered in practice. This statement applies for normal ambient temperatures (up to about 30 °C) and for high-quality mineral oils.
A ***running-in relubrication interval*** (e.g. 200 or 300 hours) is only necessary if either the inclusion of foreign bodies in the gear unit enclosure or tooth flank wear is expected. Provided the enclosure is thoroughly cleaned, the inside is coated with a fully adhesive paint and amply-sized, case-hardened and precision-machined gear wheels are used, this additional lubricant change can be omitted without detriment.

10.6 Synthetic lubricants

Apart from mineral oils, the properties of which are adequate for the majority of applications, synthetic lubricants (e.g. PGLP (polyglycole and synthetic hydrocarbons) lubricating oils are available. These have the following main ***advantages*:**

- ☐ high viscosity index (VI), thus suitable for extremely high temperature ranges,
- ☐ good oxidation and ageing stability, and hence longer service life
- ☐ lower coefficient of friction, which can contribute to reduced losses and a longer service life, above all on gear units which experience a high degree of friction (worm gears).

The ***disadvantages*** are

- ☐ they attack certain materials in the gear unit (such as the inner coating, sealing materials, plastic bearing cages, at temperatures above approximately 120 - 130 °C)
- ☐ reduced availability,
- ☐ higher price,
- ☐ polyglycoles are not miscible or compatible with mineral oils,
- ☐ special disposal requirements.

Any terms such as ***lifetime lubrication*** or ***sealed for life*** sometimes used in relation to synthetic lubricants should be viewed critically since the service intervals and service life of a gear unit do not depend merely on the lubricant.

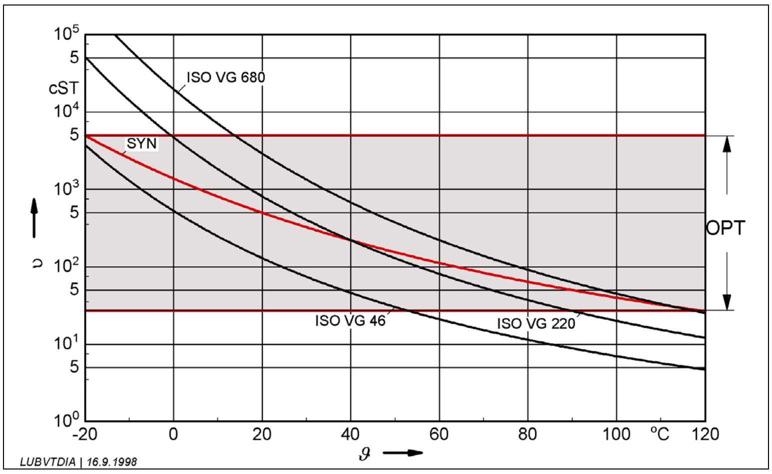


Fig. 10.6
Kinematic viscosity ν as a function of temperature ϑ (VT characteristic) of ISO VG 46, 220 and 680 mineral oils compared to a synthetic oil (SYN)

The same grade of synthetic oil can be used at temperatures from –20 °C to +120 °C in the viscosity ranged marked »OPT« (Fig. 10.6). Two viscosity grades of mineral oil would be required given the same requirements on optimum viscosity.

10.7 Lubricant quantity

Optimum ***lubricant levels*** are recommended in the literature. These are based on the modulus of the gear wheel being immersed (Fig. 10.7.1). These low immersion depths are justified for high-speed, stationary gear units where the oil level is constantly monitored. A considerably ***higher level*** has been found satisfactory for geared motors which are used under varying operating conditions (Figures 10.7.2 and 10.7.3).

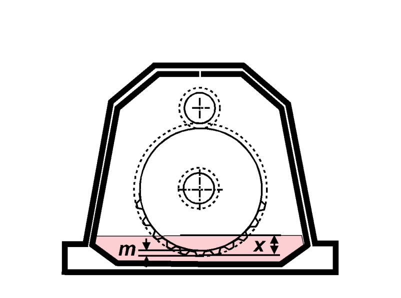


Fig. 10.7.1
Theoretical oil level (single-stage)
$x = (3 \text{ to } 5) \cdot m$

x	Immersion depth
m	Modulus

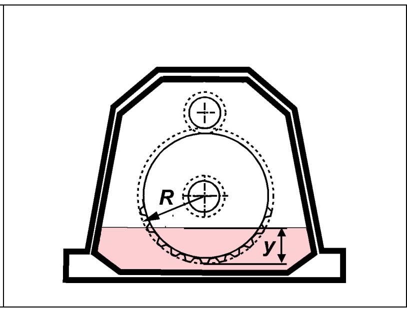


Fig. 10.7.2
Practical oil level (single-stage)
$y = 0.5 \cdot R$

y	Immersion depth
R	Radius of the gear wheel

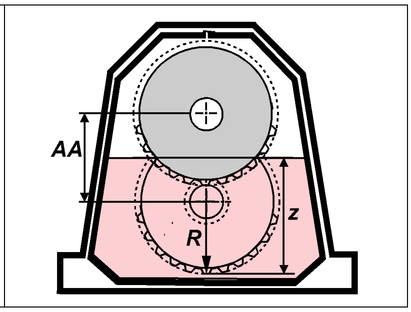


Fig. 10.7.3
Practical oil level (2-stage)
$z = R + 0.5 \cdot AA$

z	Immersion depth
AA	Shaft-centre distance

Other aspects must be considered for vertical mountings: Because the end gear wheel only rotates very slowly (e.g. at a speed of less than 1 r/min), one cannot count on wetting by turbulence or an oil mist. The oil level must therefore reach up to at least half the width of the upper gear wheel (Fig. 10.7.4).

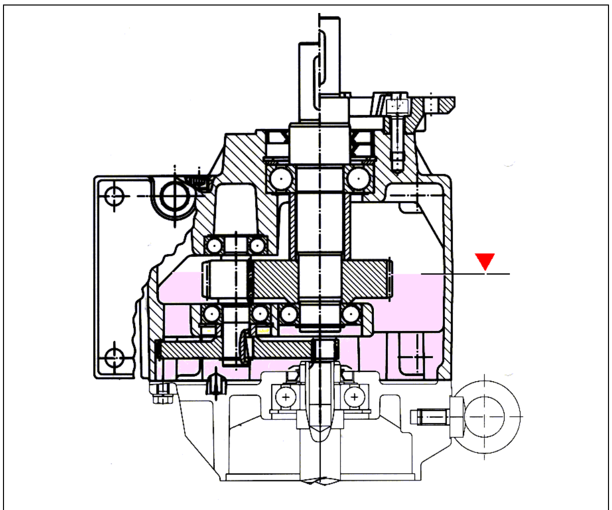


Fig. 10.7.4
Oil level for vertical mounting arrangement with output shaft aligned upwards (e.g. V6)

Upper bearings and cavities filled entirely with bearing grease

The oil volume (in kg or l) corresponding to the level is determined by experimentation of each type of gear unit in every mounting arrangement and specified in the documentation (operating instructions, catalogue, lubrication plate) (Table 10.5.5). ***Oil level inspection glasses*** or other level indicators allowing the level to be checked from the outside are only fitted in exceptional circumstances and at the express wish of the customer. The following reasons speak against the use of oil level indicators on standard geared motors:

- no access in the case of concealed installation,
- poor legibility after prolonged operating time,
- expensive and time-consuming machining of the gear unit enclosure to accommodate the mounting arrangement,
- gear unit enclosure not universal – replacement parts cannot be supplied from stock,
- operator obliged to carry out constant monitoring – additional servicing labour costs.

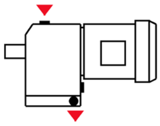
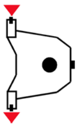
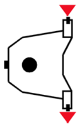
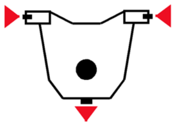
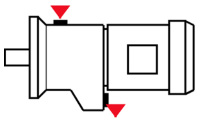
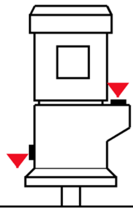
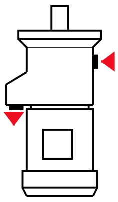
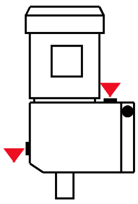
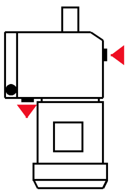
Type of construction and mounting arrangement		Gear unit type (examples)		
		G 02, G 03	G 62, G 63	G 102, G 103
IM B3		0.35	4.7	20
IM B6		0.4	5.0	21
IM B7		0.4	5.0	21
IM B8		0.4	5.0	21
IM B5		0.3	4.2	18
IM V1		0.6	8.5	37
IM V3		0.6	8.5	37
IM V5		0.7	9.5	41
IM V6		0.7	9.5	41

Fig. 10.7.5 Extract from the lubricant table of a series of helical-gear units
Lubricant quantity in kg or l as a function of the type of installation, mounting arrangement and size G of the gear unit

10.8 Lubricant change

The gear unit enclosures are equipped to allow the lubricant to be changed in situ. The holes and cover plugs are designed such that one filler plug and one or more drain plugs are accessible in any standard mounting arrangement (Fig. 10.8).

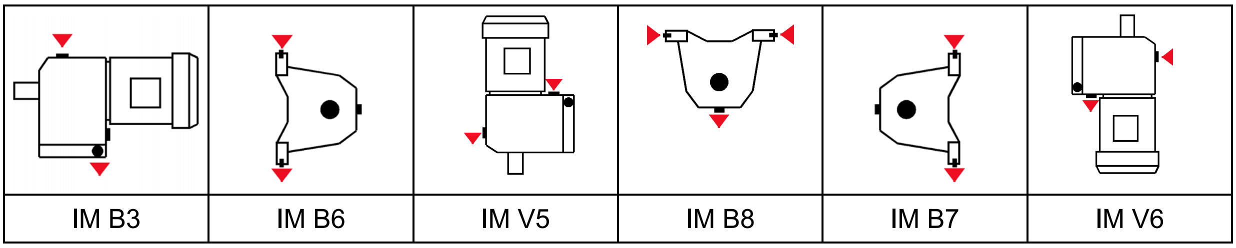


Fig. 10.8 Examples of the multiple use of standard holes in the gear unit enclosure allowing the oil to be changed in situ

A ***flushing oil*** (such as spindle oil – not degreaser, petrol or trichlorethylene) is added to the old lubricant to thin it if necessary. The mixture can be drained off after the motor has been allowed to run for a few minutes under no load. The remaining old lubricant is trapped and drained off by repeated flushing, again with the gear unit running under no load – alternating the direction of rotation if necessary.
With the motor stationary, the new lubricant is now added according to the guide values in the lubricant table in the operating instructions or the specifications on the rating plate.
It is recommended that only the ***first*** lubricant change (after 10 to 15,000 operating hours or no more than three to four years) be carried out in situ. For the ***second*** lubricant change (i.e. after approximately 20 to 30,000 operating hours), the drive should be brought into the workshop to be stripped and inspected so that any damage to the seals or bearings can be investigated. After this oil changes can alternate between being carried out in situ and as part of an inspection in the workshop.

10.9 Lubricant grades

Gearbox oils with the standardized short designation ***CLP 220*** are suitable. This designation is used by all lubricant suppliers and is specified in DIN 51517-3 with the following meaning:

C Lubricating oil

L With agents to increase the corrosion protection and/or the ageing resistance

P With agents to reduce friction and wear in the mixed-friction zone and/or to increase the load-carrying capacity

220 ISO viscosity grade ISO VG 220.

The lubricant must provide low-friction and virtually wear-free continuous running duty. The load stage at which damage is caused during the FZG test in accordance with DIN 51354 should be higher than load stage 12 and the specific abrasion should be below 0.27 mg/kWh. The lubricant must not foam or attack the inner coating, the rolling contact bearings or the gear wheels and it must protect against corrosion. Different grades of lubricant must not be mixed together, otherwise the lubricating properties could be impaired. The use of demonstrably equivalent lubricants is the only means of guaranteeing a long pot life.
Provided the ambient temperature is not below approximately –10 °C, an ISO viscosity grade of VG 220 (SAE 90 or. SAE 85W-90) is recommended, or AGMA 5 EP in North America. Oils with a lower nominal viscosity and correspondingly better starting characteristics should be used for lower ambient temperatures. For example, ISO VG 46 (SAE 75) or AGMA 1 EP. These grades may also be required at temperatures around the freezing point if the drive's breakaway torque has been reduced with a view to achieving soft starting or if the motor has a relatively low output. ISO VG 680 (SAE 140) or AGMA 8 EP oils must be used for ambient temperatures continuously above +30 °C.
The lubricant selected by the works for the initial filling is marked in the operating instructions or can be obtained by contacting the works. The operating instructions should contain a list of lubricant grades approved by the works for the ***second filling***. The extract quoted in Table 10.9 is a typical example.

Table 10.9 Lubricant recommendation for the second filling

Manufacturer	Helical gearing and bevel gearing	Worm gearing
ARAL	Degol BMB 220 or Degol BG 220	Degol GS 220
BP	Energol GR-XP 220	Enersyn SP-XP 220
CALYPSOL	Bison HSR 220 oil	Ecusynth PG 220
CASTROL	Hypoy EP or Alpha SP 220	-
DEA	Falcon CLP 220	-
ELF	Reductelf SP 220	-
ESSO	GP9O or Spartan EP220 gearbox oil	-
FINA	Giran 220	-
MOBIL	Mobilube GX 85 W-90-A or Mobilgear 630	Glygoyle 30 or Glygoyle HE 220
SHELL	Omala 220	Tivela Oil WB
TEXACO	Geartex EP-A SAE 85W-90	-

10.10 Seals

A relatively large amount of time and money needs to be spent on the design, manufacture and testing of gear units to achieve a reliable and enduring seal. Minor leaks may occur in some instances under unfavourable operating conditions. The quantity of oil lost is usually so minimal that there is never any risk of the gear unit running dry thanks to the ample quantity of oil used for the initial filling. Aside from the operational reliability of the gear unit, it should not be forgotten that production may be disrupted or jeopardized in some cases (food production, painting facilities).

10.10.1 Mating surfaces

Paintable, highly resilient chemical sealants are usually used to seal mating surfaces on the gear unit. Sealant residue must be carefully removed in the course of repairs and the mating surfaces coated with a sealant of an equivalent quality.
This method is more cost-effective for the workshop than replacing gaskets made from pressed flat material which generally have to be obtained from the gear unit manufacturer.

10.10.2 Radial shaft seals

Standardized radial shaft seals (RWD) conforming to DIN 3760 in high-quality rubbers (elastomers) are generally used. These have a bezel-shaped lip which is set onto the precision-machined shaft by pretensioning a spiral spring. The lubricant film should be parted without the rubber lip itself running entirely dry and heating up too severely. Quotation from a seal ring manufacturer: "A 100 % seal is not desirable". The apparently self-contradicting sealing process can be explained by the effect of capillary action (Fig. 10.10.2.1).

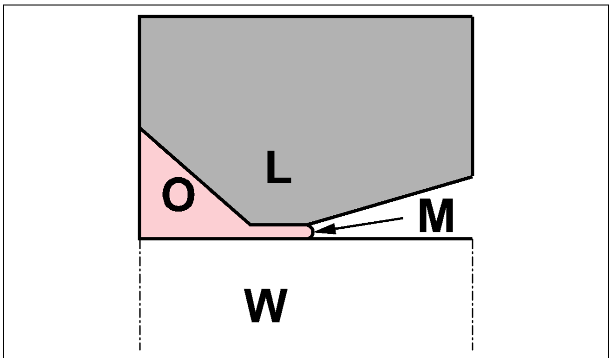


Fig. 10.10.2.1
Principle of sealing by capillary action

L Sealing lip
O Oil
W Shaft
M Meniscus in the seal gap

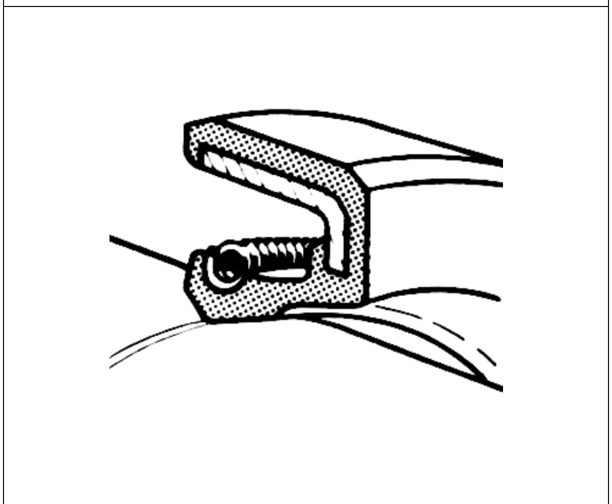


Fig. 10.10.2.2
Operation-dependent influences on the seal
thermal elongation

- ☐ material cracks
- ☐ decomposition of the compound
- ☐ change in hardness of the compound
- ☐ shaft corrosion
- ☐ lubricant failure
- ☐ ageing of the sealing lip
- ☐ nicks, slits
- ☐ stick-slip effect
- ☐ vibration
- ☐ wear
- ☐ excessive eccentricity
- ☐ enclosure leakage.

Source: GOETZE

10.10.3 Sealing between the motor and gear unit

Since wear due to temperature and time cannot be avoided, particularly on the rotor shaft seal, this sealing point is often combined with a contact-free ***labyrinth*** or ***gap seal***.

Function of this seal slinger:

- ☐ throws off oil,
- ☐ traps oil pressure,
- ☐ works like a labyrinth,
- ☐ can be changed in case of wear.

The effectiveness of this seal depends to a large extent on concentric running with the smallest possible distance from the fixed part. Particular care should be taken over these points upon reinstallation (Fig. 10.10.3).

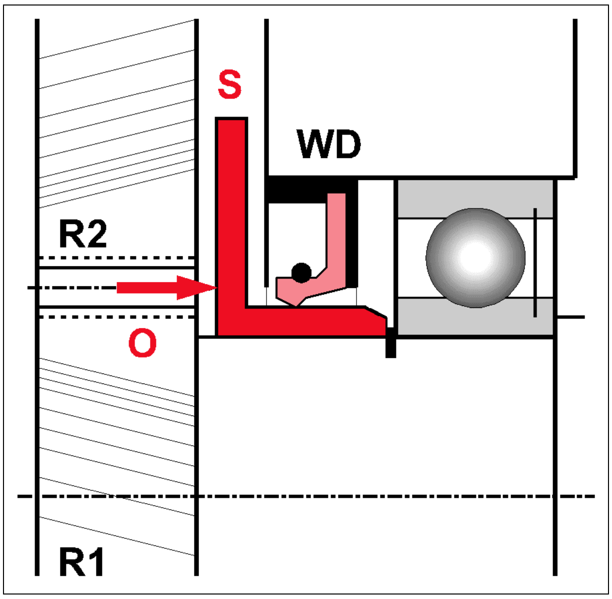


Fig. 10.10.3
Principle of the sealing between the motor and gear unit

WD	Shaft seal
S	Centrifugal disc (labyrinth plate)
R1	Pinion
R2	Gearwheel
O	Oil jet (strength and direction dependent on peripheral speed, helix angle, direction of rotation etc.)

It is also important that the shaft seal (WD) is fitted the right way round so that the rubber lip is forced against the shaft by the overpressure of the lubricant, while any dust lips must always be on the outside.

The rubbing shaft seal is a wear part and its effectiveness must therefore be checked when the lubricant is changed and it must be replaced if necessary. Fig. 10.10.2.2 uses extracts from GOETZE works documentation to show how numerous and complex the operation-dependent influences are on this component, such that global statements regarding the service life of a radial shaft seal are not possible:

Because the rubber lip of the shaft seal can also work its way into the metal, it is recommended that an easily changeable part (such as a sleeve or the centrifugal disc S shown in Fig. 10.10.3) be used as the counterpart instead of the shaft.

10.10.4 Mechanical design of the seal on the rotor shaft

Fig. 10.10.4.1 shows a complex design for the seal on the rotor shaft between the motor and the gear unit. It requires an "integral construction" in which the motor, drive-end bearing bracket and gear unit cover are integrated.

Some customer groups demand that ***standard flange-mounted motors*** be fitted onto the reduction gearing for the purposes of obtaining spare parts. Apart from the unfavourable design layout and pinion mounting, this type of standard motor either has no shaft seal at all (design 1 in Fig. 10.10.4.2) or has an ***oil-tight bearing flange*** on the shaft exit (design 2) which has none of the additional sealing functions of an integral design.

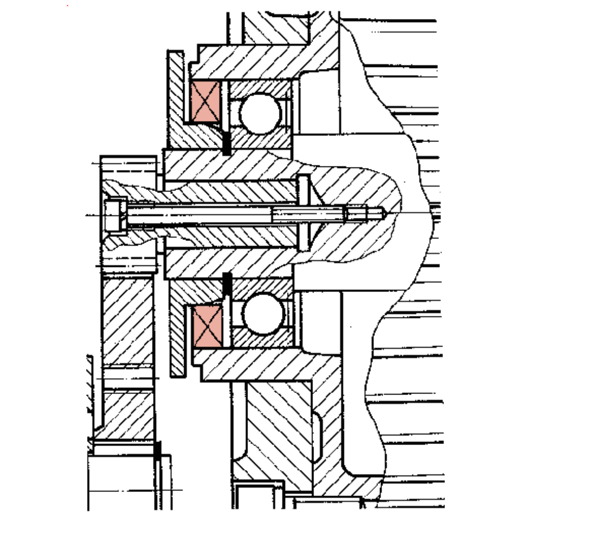


Fig. 10.10.4.1
Mechanical design of the sealing point between the motor and gear unit on a geared motor designed as an »integral unit«

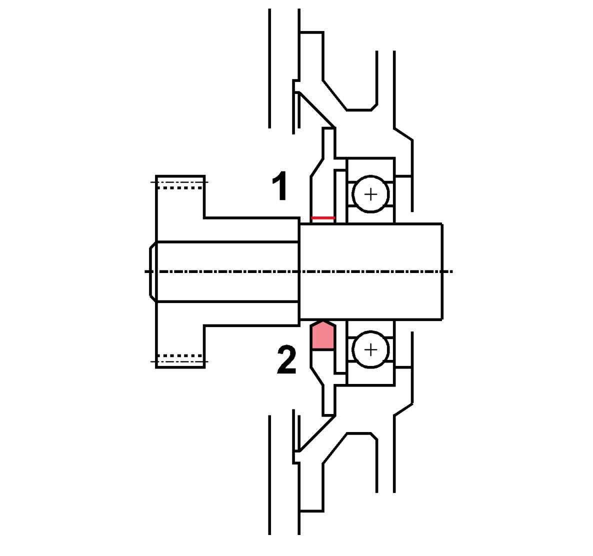


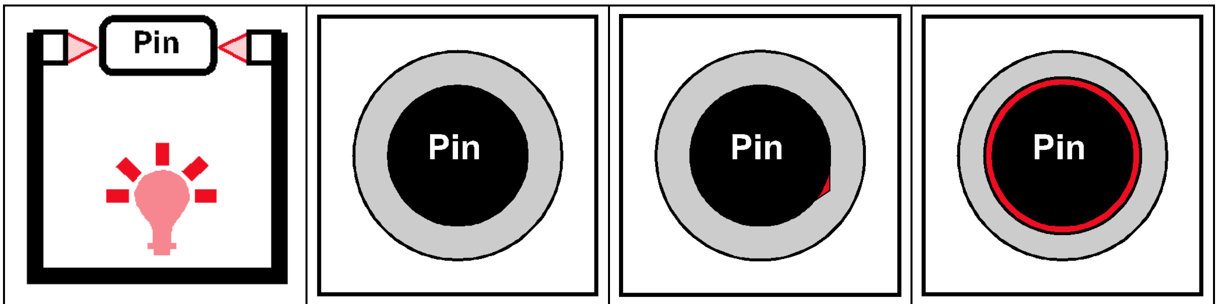
Fig.10.10.4.2
Seal on the shaft extension on a standard flange-mounted motor fitted onto reduction gearing

1 Normal design: gap seal without oil tightness

2 Special design: oil-tight bearing flange

10.10.5 Checking shaft seals

Shaft seals can only fulfil their function if the sealing lip makes contact with the entire circumference of the shaft at the correct tension. Excessive pretension results in increased heating and wear and must therefore be avoided to the same degree as insufficient contact between the lip and the shaft. Fig. 10.10.5 shows the simple and well-established ***light-gap test***.



Principle of the light-gap test	Normal mandrel diameter ***No light*** Result: good	Normal mandrel diameter ***Point of light*** Result: poor	Reduced mandrel diameter ***Round gap*** Result: good

Fig. 10.10.5 Light-gap test on shaft seals

10.10.6 Temperature application range of shaft seals

The operating temperature has a pronounced influence on the sealing action and ageing of the sealing lips. Fig. 10.10.6 shows the limits recommended in DIN 3760.

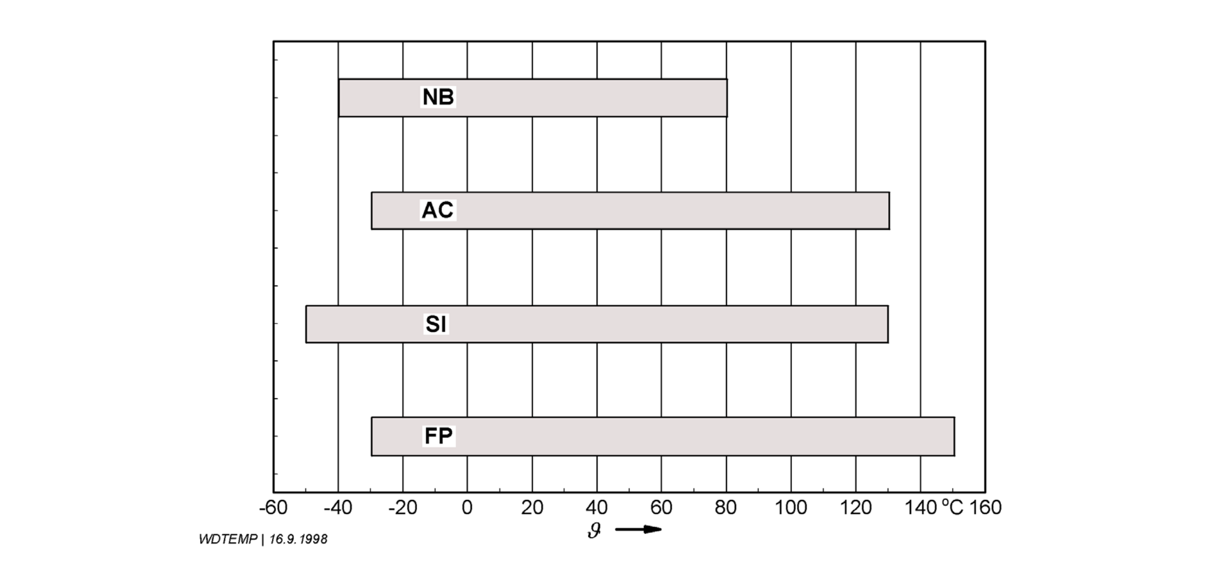


Fig. 10.10.6 Guide lines for the range of application temperatures of radial shaft seals in accordance with DIN 3760

NB (NBR)	Nitrile-butadiene rubber (standard quality)
AC (ACM)	Acrylate-butadiene rubber (standard quality)
SI (MQ)	Silicone rubber (special quality)
FP (FPM)	Fluorosilicone rubber (special quality)

10.10.7 Example of application

The application shown in Fig. 10.10.7 combines the difficulties of a mounting arrangement where the shaft is aligned vertically up (V3) with the high demands on cleanliness in a modern mill.

Fig. 10.10.7
Example of the high demands placed a geared motor's seal
Shaft aligned vertically up (V3) on cellular wheel sluices in a mill

11 Long-term mechanical overloading

Overloading on the motor winding is usually caused by the effects of temperature and time, whereas mechanical components are overloaded by forces or torques the duration of which may be extremely short. This fundamental difference must be observed in the selection of protective devices.
Two simple and cost-effective systems have proved themselves in the protection of electrical machinery windings:

- ☐ current-dependent delayed thermal overcurrent protective devices with bimetal cut-outs,
- ☐ thermal motor protection (TMS) using PTC thermistor detectors.

Both protective devices are ***temperature-dependent****:* the bimetal element reacts indirectly to the heating effect of the motor's current, the thermistor reacts directly to the winding temperature. The time-delay thus incurred is intentional. It allows the overload capacity of the motor to be exploited and prevents the protective device from tripping unnecessarily early. An electric motor's winding can be securely protected given the correct selection, installation and setting of the protective device.
However, this protection does not extend to cover the mechanical components, as the following section demonstrates. A drive with a geared motor is used to represent many mechanical transmission components (shafts, keys, bearings, couplings, belts etc.).

11.1 Torque overload due to flat current characteristic curve

On drives with a rising current characteristic curve as shown in Fig. 11.1.1, the current consumption is a very good representation of the instantaneous output of the motor and thereby the torque load on the gear unit.

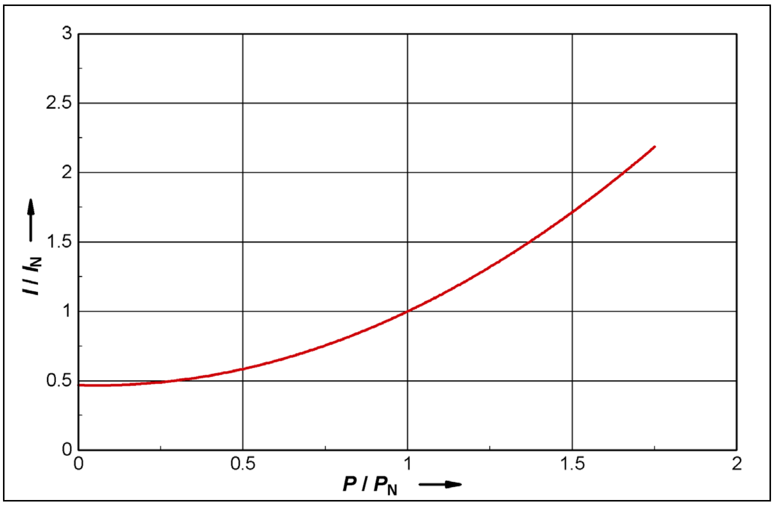


Fig. 11.1.1
Typical current characteristic for medium-size 4-pole electric motors

Above all in the case of small and low-speed motors, the current consumption is determined mainly by the magnetisation requirements. The current characteristic curve has therefore a tendency to be flat and does not offer a reliable criterion for the mechanical losses.
Considerable overloading of the gear unit can therefore occur within the tolerances specified by international standards without the motor being endangered thermally. Fig. 11.1.2 provides an example of this danger. If the relay used is at its upper tolerance limit in accordance with IEC 60292, i.e. it can permanently carry 1.15 times its set current, 1.4 times the nominal torque would be present at operating point X. While the motor is thus subjected to an approximately 15 % current overload and an approximately 30 % thermal overload, the gear unit is being expected to experience roughly a 40 % overload without the correctly installed and set motor protection relay responding.

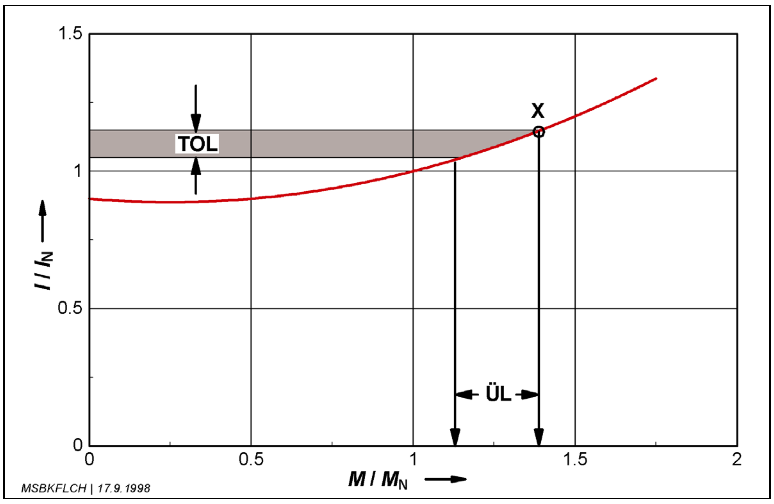


Fig. 11.1.2
Potential gear unit overload at operating point X for a relay operating current of 1.15 I_N (current characteristic curve for small or low-speed motors)

TOL Response tolerance in accordance with IEC 60292 for a motor protection relay

ÜL Possible overload range of the gear unit in the form of relative torque M/M_N

11.2 Monitoring by means of temperature sensors

Protection of the gear unit against persistent overloading by means of direct temperature monitoring of the motor windings is only possible if the motor is operating within its permitted maximum overtemperature and if the ambient temperature is close to the limit of 40 °C when the motor is working at its nominal output.
Deviations from these requirements can lead to considerable mechanical overloads on the gear unit without the thermal protection device responding.

11.2.1 Motors with large thermal reserves

The extent of effective material used is determined mainly by the required starting and pull-out torques, above all in the case of smaller motors in the lower output range, so that considerable thermal reserves are often available. Fig. 11.2.1 shows that considerable mechanical overloading of the gear unit can occur when the motor is operating at the limit temperature monitored by thermal motor protection (TMS), even at the maximum permissible ambient temperature. At a nominal load $P/P_N = 1$, the windings would have a nominal overtemperature of $\Delta\ \vartheta_N = 50$ K, which, together with the ambient temperature of $\vartheta_{amb} = 40$ °C, gives a nominal temperature of $\vartheta_N = 90$ °C. If this drive is operating at the limit temperature $\vartheta_{lim} = 130$ °C, the relative output is almost 150 % of the nominal output.

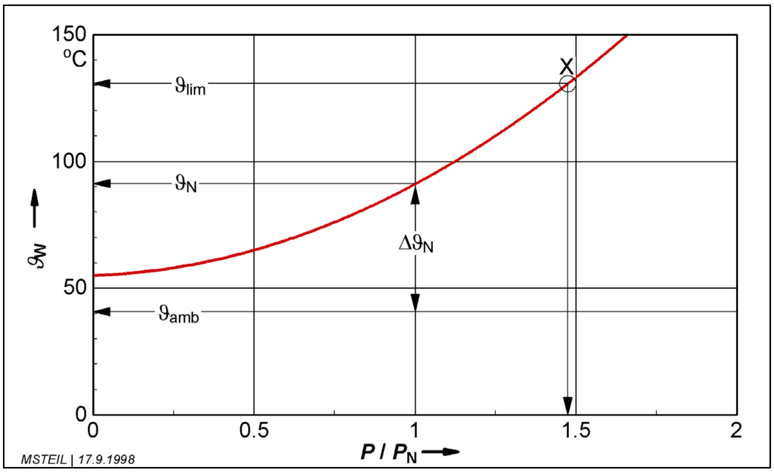


Fig. 11.2.1
Possible gear unit overload P/P_N at operating point X by exploitation of the limit temperature ϑ_{lim} on a motor with a relatively low nominal temperature ϑ_N and a maximum permissible ambient temperature ϑ_{amb}

11.2.2 Operation at low ambient temperatures

If a geared motor is operated at ambient temperatures substantially below the maximum value of 40 °C permitted by VDE regulations, full utilisation of the thermal reserves thus created leads **to *higher output***. The gear unit can be overloaded considerably as shown in Fig. 11.2.2 without endangering the motor and within the temperature limits set by the TMS.

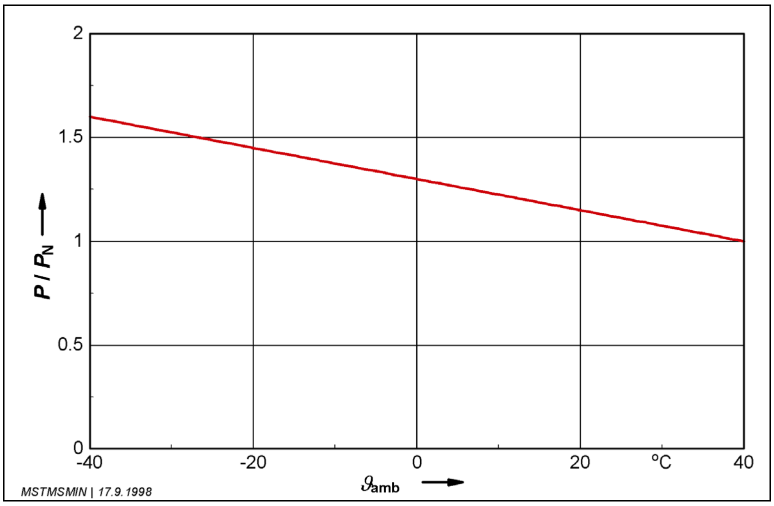


Fig. 11.2.2
Possible gear unit overload P/P_N by utilisation of the limit temperature monitored by TMS at ambient temperatures ϑ_{amb} below the standard value of 40 °C

11.3 Radial shaft loading

Standard motors are often subjected to very high radial forces on the shaft, particularly when output is provided by V-belts, and these forces are sometimes aggravated by unnecessary pretension. The permissible limit values can be obtained from the manufacturer's information. Fig. 11.3 shows that a large scatter band is present even for standard motors.
See section 8 for further information on the calculation and limit values for geared motors.

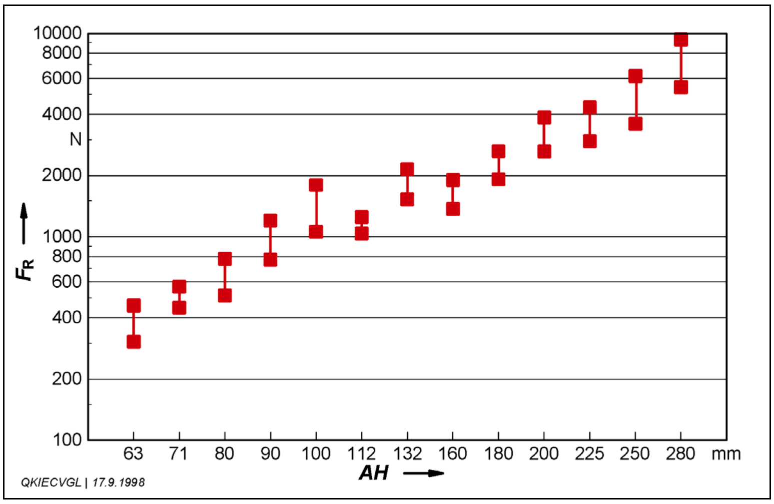


Fig. 11.3
Permissible radial force F_R on the shaft end of standard motors with shaft heights *AH* = 63 to 280 mm in the form of a scatter band according to the catalogue data of several manufacturers

11.4 Axial shaft loading

Subjective limit values for the axial load capacity of the shaft bearings cannot be specified since the overall loading on the rolling contact bearing alters according to the direction and height of the axial force, radial force and rotor weight. Tare weight constitutes a large part of the overall loading, particularly on larger machines. One manufacturer's catalogue differentiates between eight instances of loading as shown in Fig. 11.4**.**

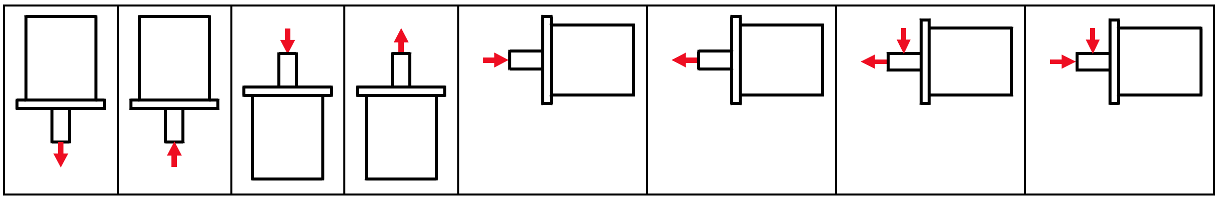


Fig. 11.4 Differentiation of eight instances of loading for the axial forces on the shaft end of standard motors (according to SIEMENS catalogue data)

12 Brief, controlled torque shocks

This section will deal with the mechanical effects of the relatively slow subsiding (quasi-static) torque shocks which are to be expected during operation. ***The level and duration of these shock loads are controlled.***

12.1 Definition

- ☐ Torque generated in the motor is within the ***overload capacity*** limits for standard three-phase current motors, i.e. at least 1.6 times the rated torque [1.6] standard, and usually 2.5 to 3 times in accordance with the rated torque maximum (see Fig. 5.1.2.4).
- ☐ In the case of a monitored overload, no significant, ***dynamic*** mass impact generated torque peaks are created.
- ☐ Appropriate currents, the ***thermal*** effects of which limit ***the duration of the overload*** via the means described in section 6, are required to generate the torque.

In the context of this definition, "uncontrolled" however refers to torque generated by the motor's ***regenerative reverse braking***, since the relatively low thermal effect the cannot adequately recorded by the overload protection device.
Torque shocks of up to 8 times the rated torque can occur in pole-changing motors (see Fig. 5.3.8.4). Depending on the external mass : rotor mass relationship, a greater or lesser component of this braking torque flows outside via the shaft and the power transmission components (Figures 12.1.1 and 12.1.2). If there are high inertia factors (e.g. *FI* > 2) and reverse braking often occurs during operation, clarification from the manufacturer of the motor and the power transmission components is recommended.
The ***Factor of Inertia FI*** is the relationship between all masses driven by the motor, including the motor rotor's inertia, converted to the motor speed, to the motor rotor's inertia, thus

$$FI = \frac{J_{total}}{J_{rot}} = \frac{J_{ext} + J_{rot}}{J_{rot}}$$

The acceleration torque developed by the motor distributes itself over the masses in a linear fashion: This rule is primarily significant for the ***loading of driven power transmission components*** – e.g. gear unit.

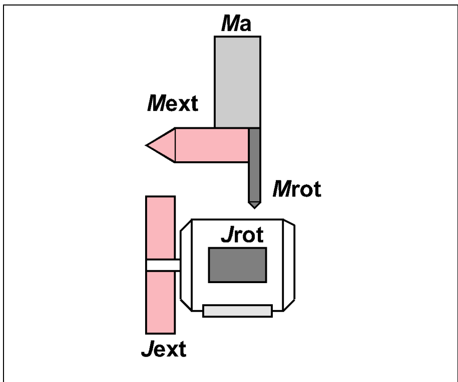


Fig. 12.1.1
Torque flows to mass

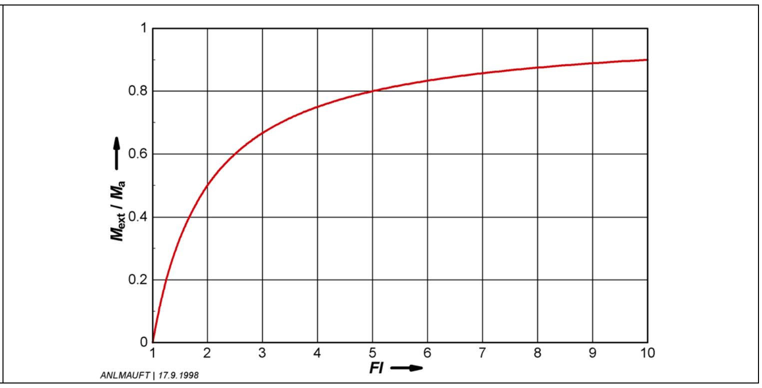


Fig. 12.1.2
External component of the torque

The component of the acceleration or deceleration moment which flows outside is shown in diagram 12.1.2; it is calculated from

$$\frac{M_{ext}}{M_a} = \frac{J_{ext}}{\Sigma J} = \frac{J_{rot} \cdot (FI - 1)}{J_{rot} \cdot FI} = \frac{FI - 1}{FI}$$

This examination makes it clear why the factor of inertia *FI* has a fundamental function in ***shock classification*** determination. The shock classification determines the service factor for choice of a gear unit.

12.2 Mechanical motor components

Brief, controlled torque shocks according to the definition given in section 12.1 can generally be absorbed by the mechanical components of an electric motor (shafts, keys, bearings) without damage, since these components are mostly generously dimensioned.

12.3 Gear unit and other mechanical power transmission components

The torque shocks for these components are taken into account with a ***shock classification*** within the system of a ***service factor*** which, although not standardized, is usual with most manufacturers.
Power transmission components which are offered as standard (couplings, chain wheels, gear units) must be adapted to differing load conditions. The examples shown in Figures 12.3.1 and 12.3.2 indicate this wide span.

Service factor
in terms of
time

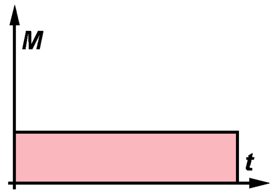
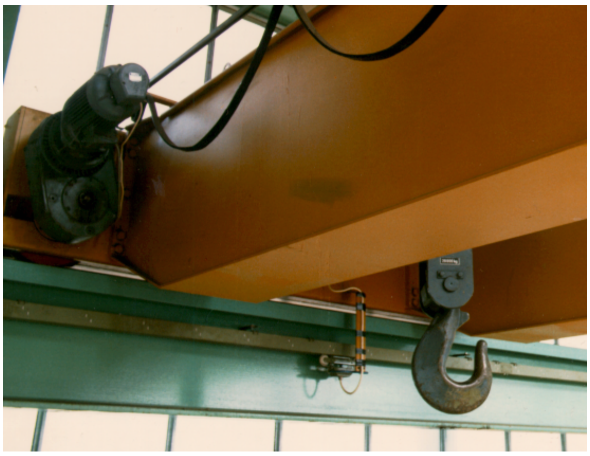


Fig. 12.3.1
Aerator for enriching drinking water reservoir with oxygen.

Continuous running duty:
24 hours per day,
365 days per year



Service factor
in terms of
torque

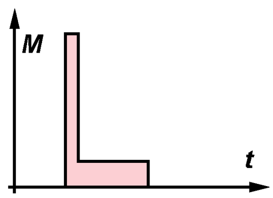


Fig. 12.3.2
Power station crane for turbine and generator overhauls

Short-time duty:
Few minutes per year

In order to be able to compare both drive cases, a ***fictitious torque*** (Fig. 12.3.3) must be formed and compared. These torques, calculated from the actual load population, should be equivalent, e.g. in continuous running duty they should lead to the same service life for corresponding gearbox size as loading with the actual torque.
The withdrawn code of practice VDI 2151 gave the following analogous definition of the service factor:
The service factor f_B is the number by which the rated torque M_L of the driven machinery must be multiplied in order to achieve a fictitious torque M_N which guarantees the same safety from gear unit damage as the actual effective torque which changes with time, but via action on the gearbox output shaft which is constant over time and may be of any duration.
The gear unit is correctly designed if its continuous loading capacity is equal to the fictitious torque M_N.

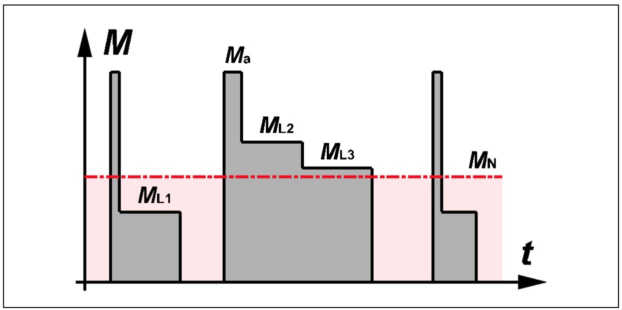


Fig. 12.3.3
Definition of the service factor
M_a acceleration torque
M_L load torque, 1, 2, 3
M_N fictitious nominal torque (rated torque) for equivalent continuous load with the same lifetime and safety

The formation of an equivalent rated torque from the load population M_a, M_{L1}, M_{L2}, M_{L3} taking account of the action times of each and the total running time requires considerable calculation effort. In the usual simplified processes for geared motors and other power transmission components, the torques which go beyond nominal torque of the *driven machinery* (e.g. M_a, M_{L2} and M_{L3}) are recorded and taken into account in terms of the ***shock classification***.
The shock classification is intended, above all, to take account of a known or foreseeable torque increase, which is caused by the usual method of operation of driven machines. Such overloading can, for example, occur as a result of
- ☐ sluggishness at low ambient temperatures,
- ☐ initial resistance from viscous agitated medium,
- ☐ occasional transport of super heavy bulk cargo,
- ☐ hard spots in the peeling of bark from tree trunks,
- ☐ crushing of hard material in the designated use as a crusher or mixer.

In accordance with this definition, overloads with shock level III are limited to double the rated torque – this limit arises from consideration for the external transmission components and the design of the driven machine.
In contrast to almost all standard or usual systems for determining the service factor, clear objective limit values should be given for the shock classification [2.9], rather than concepts which are open to subjective interpretation. (Table 12.3.4).

Table 12.3.4 Shock classifications in subjective description and objective determination

Shock classification	Description	Short-term permissible load
I	uniform, without shock loads	$M/M_N \leq 1$
II	moderate shock loads	$1 < M/M_N \leq 1.6$
III	heavy shock loads	$1.6 < M/M_N \leq 2$

Under no circumstances can the shock classification and a corresponding service factor accommodate extreme overloads which can arise from improper use of a driven machine, e.g.
- ☐ blockage of a crusher by pieces which are too big or too hard,
- ☐ impact of a crane chassis on a buffer,
- ☐ start up of a mixer on solidified material,
- ☐ blockage of a chain drive by foreign objects.

Torque peaks which result from an occurrence of this type which was not foreseen, or takes the form of a blockage, can only be reduced using mechanical overload protection (slip clutch, hydraulic clutch, slip hub, shear pins) (see section 13).

12.4 Service factor for motors

The ***service factor*** of geared motors is always (in Europe) and generally (in North America) considered to be a ***mechanical*** rating of the gear unit – (i.e. in the sense specified in section 12.3). In North America, however, there is also a ***service factor SF for electric motors*** which is stated by some manufacturers on the motor's rating plate, and which can then be wrongly interpreted for geared motors.
There is, in fact, a clear definition in NEMA MG1-1.42: "The service factor of an AC motor is a multiplier which, when applied to the rated horsepower, indicates a permissible horsepower loading which may be carried under the conditions specified for the service factor (see 14.36)".
It is stated in particular, that

- increased output is possible in continuous running duty,
- the winding temperature in this operation may be 10 K higher than the temperature class assigned (NEMA MG1-12.42.1.b),
- efficiency and power factor change,
- Service factor >1.0 may only be used in ***open-circuit air-cooled (ODP) motors***.
- Totally enclosed fan cooled (TEFC) motors have a service factor of 1.0.

Despite these specifications, service factor SF is one of those NEMA specifications that is often misunderstood. In the USA, for example, it is often applied to ***closed standard motors*** (TEFC), if they are insulated with temperature class F insulating materials, but are used according to class B (usual rating SF = 1.15).
It is clearly stated in NEMA MG1-10.38 that the ***Service Factor SF*** shall be stated ***on the rating plate*** only in case it is different from 1.0, e.g. not in case of TEFC (IP54) motors.

13 Extreme torque peaks

In our context, ***extreme torque peaks*** are understood as sudden overloads ***far in excess of the maximum torques developed by the motor*** which can therefore damage the power transmission components even if normal safety factors are included in the design.

13.1 Mechanical output and electrical input

There is a fixed relationship between mechanical output and electrical power input for every type of motor under ***stationary*** operation (see section 5.1.1). This load characteristic, which is determined by measurement for every standard motor type and can be obtained from the manufacturer, enables the degree of loading to be ascertained with certainty on the basis of a simple operational measurement. Of course, this must also take into account the most unfavourable operating conditions.
This simple procedure does not apply to ***abrup****t* processes because the flywheel energy of the rapidly-revolving motor rotor comes into effect during sudden braking of the slow-running shaft and tries to maintain the existing conditions of movement by means of moments and forces which are greater, the more rapid the change in speed.
These processes are independent of the speed-torque characteristics of the motor and require no energy from the mains supply and so cannot even be shown on extremely fast ***electric*** input plotters.
It should also be clear from Fig. 13.1 that although the breakaway torque $M_A = 1$ is represented by a corresponding electrical input P_{el} during the starting cycle, whereas if a peak torque $M_{max} = 2M_A$ occurs during a sudden load surge P_{crit}, there is no correspondingly high indication in the electrical input.
Such peak torques can only be recorded by ***direct torque measurement*** (e.g. using a torque meter or a strain gauge) but this represents a considerable expenditure on measuring equipment and requires direct intervention in the shaft assembly.
Apart from the need for a thermal time constant for overcurrent relays and TMS, as shown in section 6, it is evident from the discussion in this section that ***it is not possible to detect and prevent abrupt overloading of the gear unit by electrical means.***

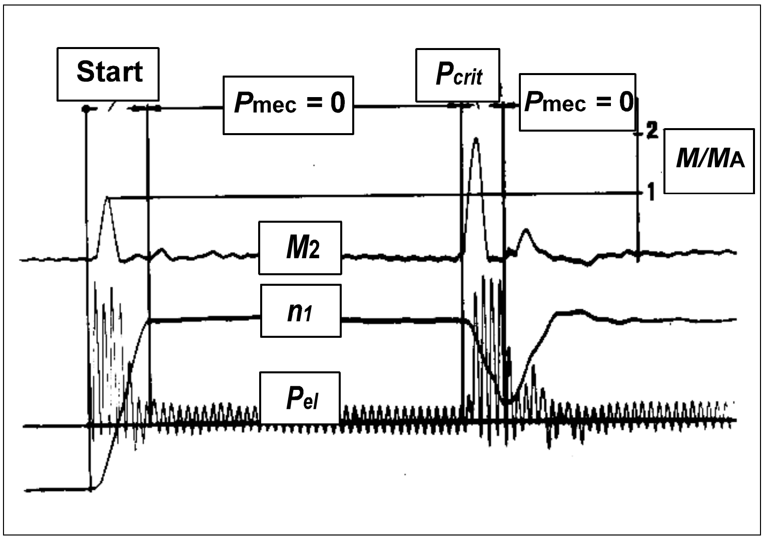
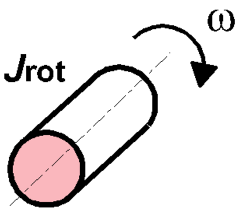
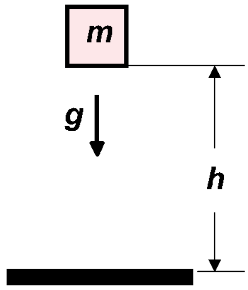
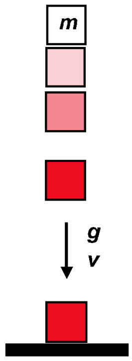
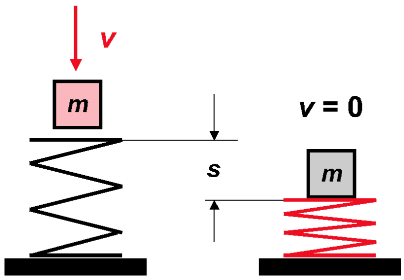


Fig. 13.1
Comparison of the electrical input P_{el} with the mechanical torque output M_2 during a starting cycle (Start) and a load surge P_{crit} ***imposed by the stored energy of the rotor***

13.2 Forms of mechanical energy

The preceding sections have shown that the abrupt overloading from mechanical components is fed from the kinetic energy stored in the rotor.
Mechanical energy can take different forms (Table 13.2):

Table 13.2 Forms of energy

Form of energy	General representation	Formula
Kinetic energy of a rotating mass (rotational energy)		$W_{rot} = \frac{J \cdot \omega^2}{2}$
Potential energy		$W_{pot} = m \cdot g \cdot h$
Energy of a mass moving linearly (kinetic energy)		$W_{kin} = \frac{m \cdot v^2}{2}$
Deformation of a spring		$W_{feder} = \frac{F_{max} \cdot s}{2}$

Explanation of the abbreviations:

W	Work (energy)	in	Nm
J	Mass moment of inertia	in	kgm²
α	Angular velocity	in	1/s
m	Mass	in	kg
g	Acceleration due to gravity	in	m/s²
h	Height (position)	in	m
v	Linear velocity	in	m/s
F	Force	in	N
s	Spring deflection	in	m

13.3 Flywheel energy = damage potential

A sample calculation should serve to clarify the amount of energy (= destructive work) stored in the rotating mass of a medium-size electric motor.
This energy can be released without the motor being "resupplied" from the mains. It is also experienced if the motor is ***disconnected from the mains supply*** shortly before mechanical locking.

If we assume:	standard 4 -pole motor	P_N	= 7.5 kW
	No-load speed	n	= 1500 r/min
	Mass moment of inertia	J_{rot}	= 0.045 kgm²

Kinetic energy of the rotating rotor mass

$$W_{rot} = \frac{J_{rot} \cdot \omega^2}{2} = \frac{J_{rot} \cdot n^2}{182{,}5} = \frac{0{,}045 \cdot 1500^2}{182{,}5} = 555\ \mathrm{Nm}$$

$$\omega = \frac{\pi \cdot n}{30}$$

To illustrate, this energy can be converted into a ***mass*** which has potential energy through being raised to a height of 1 m :

$$W_{rot} = W_{pot} = m \cdot g \cdot h$$

$$m = \frac{W_{rot}}{g \cdot h} = \frac{555\ \mathrm{Nm}}{9{,}81\ \frac{\mathrm{m}}{\mathrm{s}^2} \cdot 1\ \mathrm{m}} = 56{,}6\ \frac{\mathrm{N \cdot s^2}}{\mathrm{m}} = 56{,}6\ \mathrm{kg}$$

If the "equivalent mass" of 56.6 kg free-falls from a height of 1 m, the ***impact speed*** can be calculated in two ways:

$$v = \sqrt{2 \cdot g \cdot h} = \sqrt{2 \cdot 9{,}81 \frac{\mathrm{m}}{\mathrm{s}^2} \cdot 1\ \mathrm{m}} = 4{,}43\ \frac{\mathrm{m}}{\mathrm{s}}$$

or

$$W_{pot} = W_{kin} = \frac{m \cdot v^2}{2}$$

$$v^2 = \frac{2 \cdot W}{m} = \frac{2 \cdot 555\ \mathrm{Nm}}{56{,}6\ \mathrm{kg}} = \frac{1110\ \mathrm{kgm \cdot m}}{56{,}6\ \mathrm{kg \cdot s^2}} = 19{,}61\ \frac{\mathrm{m}^2}{\mathrm{s}^2}$$

$$v = \sqrt{19{,}61 \frac{\mathrm{m}^2}{\mathrm{s}^2}} = 4{,}43\ \frac{\mathrm{m}}{\mathrm{s}}$$

Considerable ***deformation energy*** is released upon impact of the “equivalent mass” of 56.6 kg at a speed of 4.43 m/s.
The maximum force F_{max} depends on the stiffness of the “spring”.

Let us make two assumptions:

a) Resilient rubber buffer with a spring defection s = 10 mm

$$F_{max} = \frac{2 \cdot W}{s} = \frac{2 \cdot 555\,\text{Nm}}{0{,}01\ \text{m}} = 111\ 000\,\text{N} = 11{,}3\ \text{tons (force)}$$

b) Metal-to-metal (e.g. key in a keyway) with deformation s = 0.2 mm

$$F_{max} = \frac{2 \cdot W}{s} = \frac{2 \cdot 555\,\text{Nm}}{0{,}0002\ \text{m}} = 5550 \cdot 10^3\ \text{N} = 566\ \text{tons (force)}$$

It is clear that the deformation of the key connection would not be restricted to the assumed deformation of a mere 0.2 mm under such forces. Inevitably the keyway, key and shaft will be totally destroyed.

13.4 Mechanical overload protection

The following conclusions may be drawn:

- ☐ Thermal overload protective devices reliably protect the windings but, for physical reasons, cannot protect mechanical components against abrupt overloading.
- ☐ Extreme forces may be generated from the flywheel energy of the rotating rotor of an electrical machine in the event of locking; this inevitably leads mechanical components (shafts, keys, clutches) being damaged.
- ☐ Reliable overload protection for mechanical components cannot be provided electrically, but is only be achieved by placing a mechanical limitation on the torque peaks (e.g. through slip clutches, highly resilient transmission components or spring buffers).

See [2.5], [2.6], [2.9] for more information on this topic.

13.5 Shock-amplifying power transmission components

Three-phase asynchronous motors are fast starters – particularly under no-load starting. Even a ***low level of backlash*** in the transmission path, multiplied by the gear reduction ratio, provides the free travel required for "no-load starting". ***Torque peaks of up to 18 times the rated torque*** have been demonstrated, depending on the hardness of the stop.

13.5.1 No-load/run-up time

The familiar relationship applies for the run-up time with reference to the torque characteristics given in Fig. 13.5.1.1.

$$t_a = \frac{J \cdot n}{9{,}55 \cdot M_a}$$

t_a	Run-up time in s
J	Mass moment of inertia in kgm^2
n	Speed in 1/min
M_a	Acceleration torque in Nm

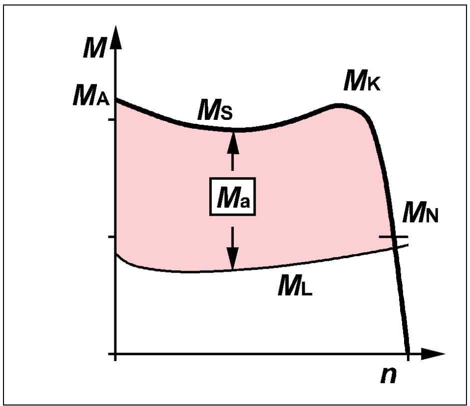


Fig. 13.5.1.1
Typical torque/speed characteristic curve for a cage motor with the characteristic values

n	Speed
M	Torque
M_N	Rated torque
M_A	Breakaway torque
M_K	Pull-out torque
M_S	Saddle torque
M_L	Load torque
M_a	Acceleration torque

Normal three-phase asynchronous motors reach full speed within fractions of a second under no-load starting, i.e. starting at no load and with no external mass moments of inertia.
Typical values for the no-load/run-up time of standard motors are given in Fig. 13.5.1.2.

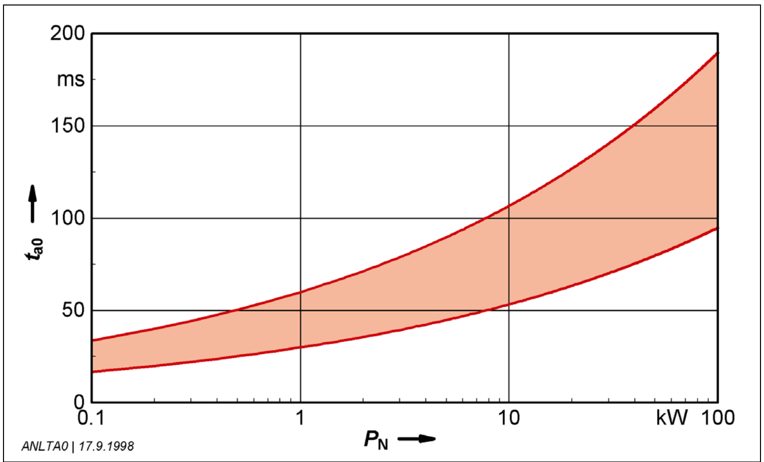


Fig. 13.5.1.2
Guide values for the no-load/run-up time t_{a0} of standard geared motors with rated output P_N

13.5.2 No-load/run-up travel

A three-phase asynchronous motor's rotor requires surprisingly little travel to reach full speed under no-load starting; most standard motors run for less than one revolution of the rotor during the acceleration period.

At constant angular acceleration, i.e. constant speed increase from 0 to n_1,

$$\varphi_{a01} = \frac{\omega_1 \cdot t_{a0}}{2} = 3 \cdot n_1 \cdot t_{a0}$$

φ_{a01} No-load/run-up travel of the rotor shaft in °
ω_1 Angular velocity of the rotor in °/s

$$1\,°/\mathrm{s} = \frac{\pi}{180}\,\mathrm{rad/s}; \quad 1\,\mathrm{rad/s} = 57{,}4\,°/\mathrm{s}$$

n_1 Speed of the rotor in r/min

t_{a0} No-load/run-up time in s in accordance with Fig. 13.3

Typical values for the rotor no-load/run-up travel of standard motors are given in Fig. 13.5.2. This gives the no-load/run-up travel of the output shaft

$$\varphi_{a02} = \frac{\varphi_{a01}}{i} = \varphi_{a01} \cdot \frac{n_2}{n_1}$$

n_2 Speed of the output shaft in r/min
φ_{a02} No-load/run-up travel of the drive shaft in °
i Reduction ratio

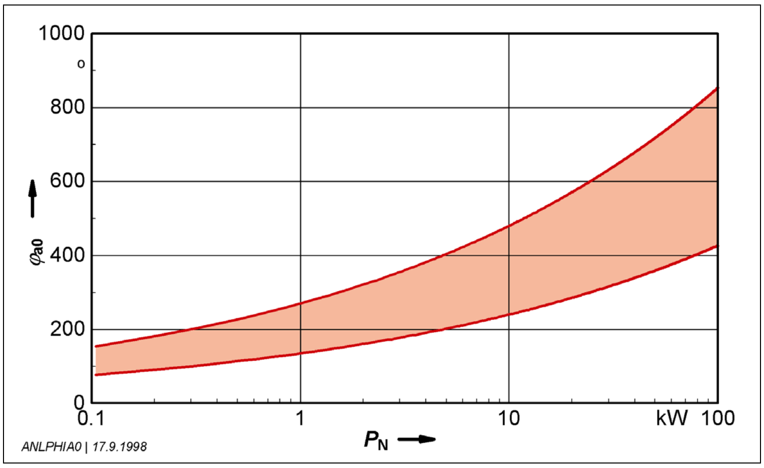


Fig. 13.5.2
Guide values for the no-load/run-up travel φ_{a01} of standard motors with reference to the rotor shaft

About 5 to 15° of free travel is required on the output shaft for the common reduction ratio i ≈ 30 (for the output shaft speed of approximately 50 r/min as frequently required) to provide the motor with "no-load starting", even though a load is actually coupled.
A backlash of this order of magnitude is very common for chain drives and also, unfortunately, for some coupling types – especially following a prolonged service life.

13.5.3 Experimental results

The measuring technology used to record torque peaks is very complex: Either ***strain gauges*** must be stuck in place and connected with sliprings or the shaft assembly must be interrupted on the output side of the gear unit so that a ***torque measuring hub*** can be inserted. The following measurements were obtained with this type of arrangement (Figures 13.5.3.1 to 13.5.3.3). The clutch with rotational play heavily increased over operational conditions used for the measurements is shown in Fig. 8.1.2.

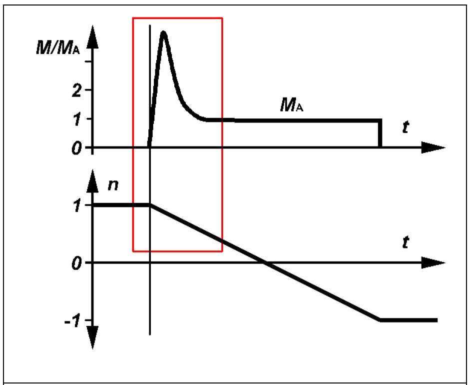


Fig. 13.5.3.1
Diagram of a reversing operation

The section highlighted is represented in oscillograms 13.5.3.2 and 13.5.3.3 by direct recording of the torque peak *M* (using a measuring hub) and the speed *n* (using a tacho) over time *t* with an x-y plotter.

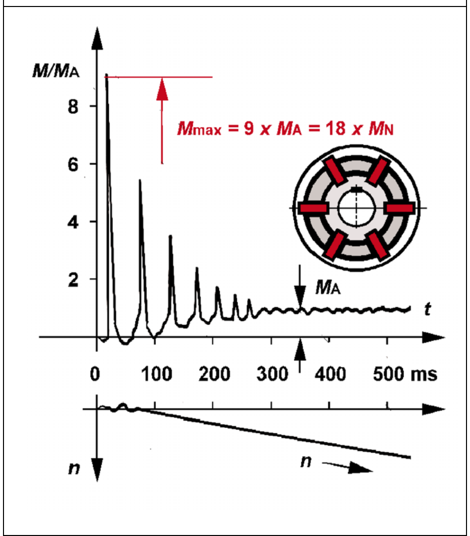


Fig. 13.5.3.2
Torque peak generated from the kinetic energy (M_{max}) compared to breakaway torque (M_A) developed by the motor for a reversing operation with a claw clutch with play as shown in Fig. 8.1.2

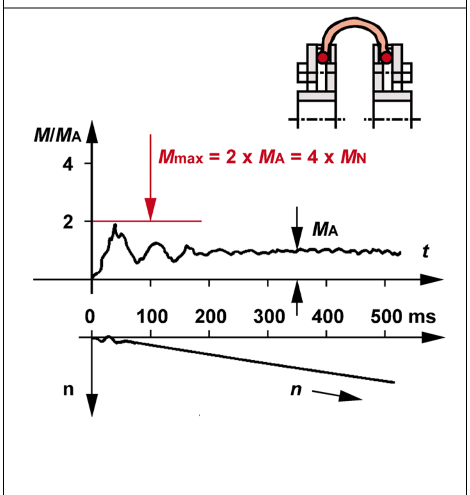


Fig. 13.5.3.3
Torque peak generated from the kinetic energy (M_{max}) compared to breakaway torque (M_A) developed by the motor for a highly resilient zero-play shaft tyre coupling as shown in Fig. 8.1.3 and Ref. A in Table 8.1.4

13.6 Shock-absorbing power transmission components

In addition to the familiar and sometimes expensive mechanical overload protection devices (for example those based on slip clutches, shear pins, ratchets, fluid), one solution ought to be mentioned in this context as its has already proved its ability to absorb shocks under reversing operations as shown in Fig. 13.5.3.3.
If the resilient element permits extremely high rotation, it can absorb the flywheel energy of the motor rotor and even replicate the action of a friction clutch. Fig. 13.6.1 shows the torque peaks absorbed by a torque hub recorded on a plotter for a hard steel on steel blocking. If a highly resilient ***shaft tyre coupling*** is connected into the torque flow under otherwise constant conditions, the torque peak is reduced considerably as shown in Fig. 13.6.2.

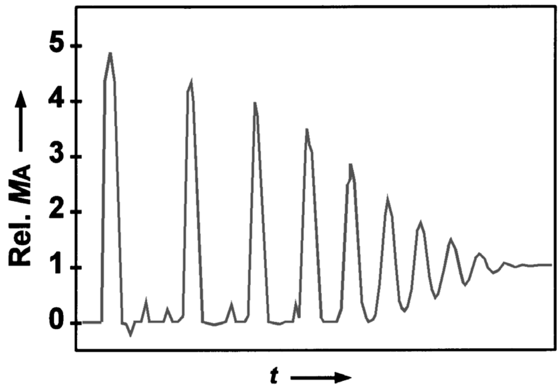


Fig. 13.6.1
Torque peaks for hard steel-on-steel locking

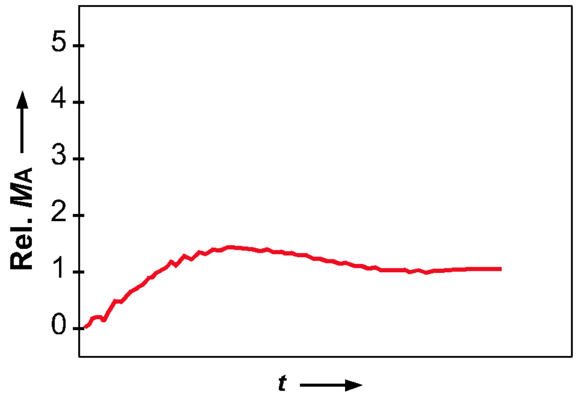


Fig. 13.6.2
Torque damping for soft locking by interpolation of a highly resilient shaft coupling

Fig. 13.6.3 shows the principle and application of a highly resilient shaft coupling which uses a rubber tyre as the power transmission component.

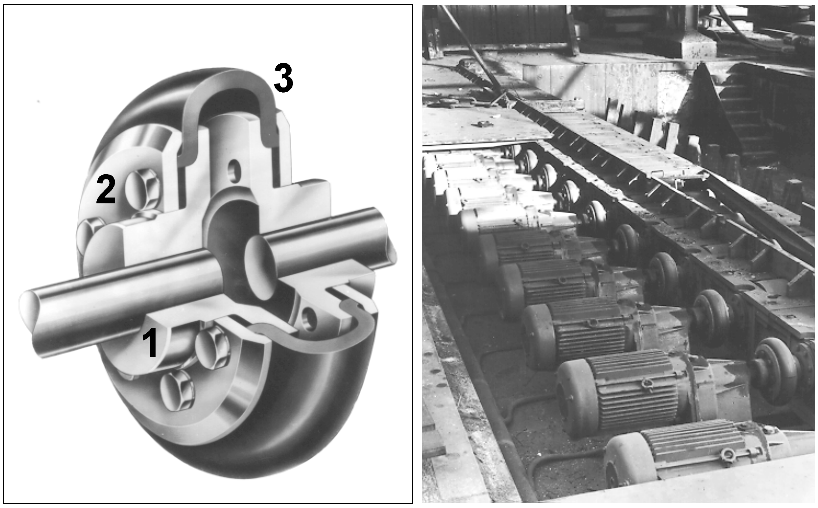


Fig. 13.6.3
Highly resilient zero-play coupling comprising a hub (1), thrust piece (2) and rubber shaft tyre (3) with fabric inlay (PERIFLEX system, manufactured by STROMAG)

Principle (left)
and application of a billet shear roller table (right)

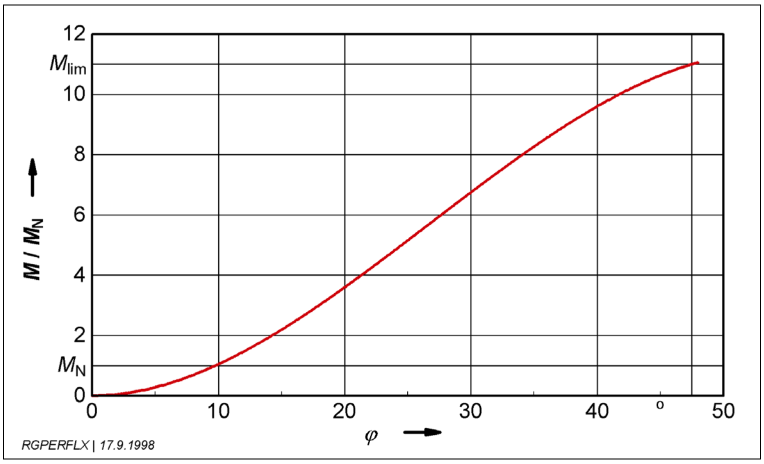


Fig. 13.6.4
Typical torsion characteristics of a highly resilient coupling with shaft tyre
(PERIFLEX system, manufactured by STROMAG),
torsional offset φ as a function of the torque M up to failure M_{lim}

Fig. 13.6.4 is representative for this type of coupling and shows that very high levels of torsion φ can occur before the rubber tyre tears. The precondition for a ***reduction in torque peaks*** is thus given. If, in an emergency, the coupling takes on the function of shear pins or a slip clutch, the loss of the shaft tyre seems insignificant by comparison with the damage which would otherwise be caused to the gear unit or the driven machinery.
As Fig. 8.1.3 shows, the shaft tyre is easily replaced without dismantling the drive or driven machinery.
The shock-absorbing action of the highly resilient shaft tyre can be explained by the following relationships: The ***rotational energy*** in the electric motor's rotor is converted into ***deformation work*** if the rotor locks:

$$\boldsymbol{W} = \frac{\boldsymbol{J}_{\mathrm{rot}} \cdot \boldsymbol{\omega}^2}{\mathbf{2}} = \frac{\boldsymbol{M}_{\mathrm{max}} \cdot \boldsymbol{\varphi}}{\mathbf{2}}$$

W	Work (energy)
J_{rot}	Mass moment of inertia of the rotor
ω	Angular velocity of the rotor
M_{max}	Maximum shock torque at the end of the resilient torsion
φ	Resilient torsional offset

As the work W (and consequently the area of the “shock load triangles” in Fig. 13.6.5) is constant, the maximum shock torque M_{max} at the end of the torsional offset is lower the greater the resilient deformation φ.

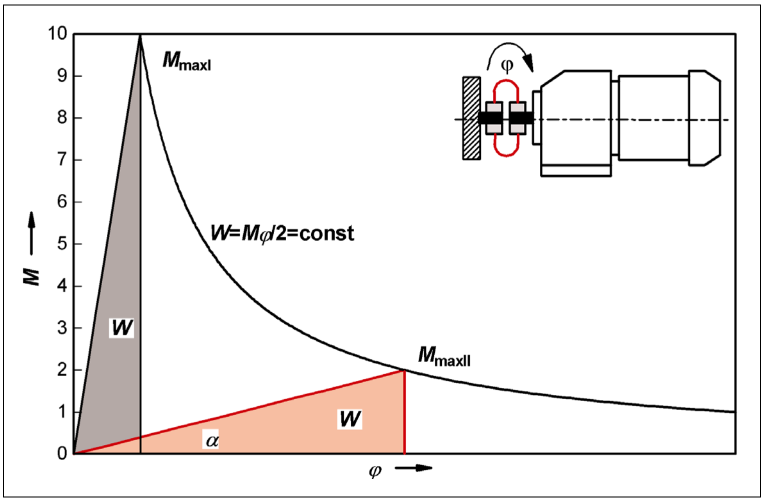


Fig. 13.6.5
Maximum shock torques M_{max} as a function of the resilient deformation φ of couplings with different torsional stiffnesses tan α under the absorption of a given amount of kinetic energy W

13.7 Switching in phase opposition

In the above discussions, the quasi-steady state was assumed for the inrush current and breakaway torque. The “old” German standard VDE 0530 Part 1/1.66 still defined these values as being applicable "after ***transient conditions*** had decayed". This clearly indicated that ***peak values*** before the onset of the steady state were to be ignored, although such peaks will always be present (Fig. 13.7). Because the transients decay after a few half cycles, their thermal effect can be ignored. However, for very sensitive electronic or mechanical components, it is very important to know the potential magnitude of the peak values. Their evaluation is extremely difficult to measure; result values fluctuate accordingly in the literature:

- ☐ Peak current value I_{max} (2 to 5)·I_A,
- ☐ Peak torque value M_{max} (3 to 6)·M_A.

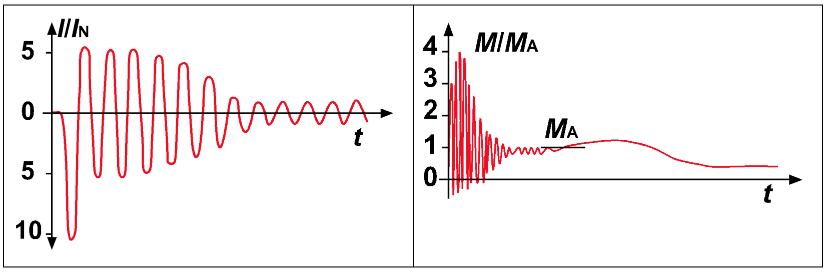


Fig. 13.7
Peak values when switching on, before the transients die away to the steady state
Left: current
Right: torque

Switching in phase opposition is a special instance of the processes described above. Power plant specifications sometimes require motors to be able to withstand a sudden switch to an independent supply in phase opposition. According to figures in the literature, this can be expected to produce a peak torque of 8 to 10 times the rated torque. This represents an exceptionally heavy load on the mechanical transmission components. This requirement is excessive and is not justified by actual conditions found in practice since, before switching to an independent supply, the motor will be properly synchronized and even in the event of emergency switching will have been reduced to a 20° phase angle and optimized to about 40 % of the residual voltage.
However, phase opposition can also occur in industrial applications if the mains supply is interrupted very briefly (e.g. for a few milliseconds). In this case the motor will be generating a reducing frequency from its remanence voltage and can be re-energized from the restored mains voltage in phase opposition – albeit with reduced amplitude. The torque peaks can then reach 3 to 8 times the rated torque.

13.8 Star-delta-starting is not a soft starting method

Initial peak values of torque and current are inadequately dampened if a motor is Y-Δ-started against heavy or full load (Fig. 13.8.1).

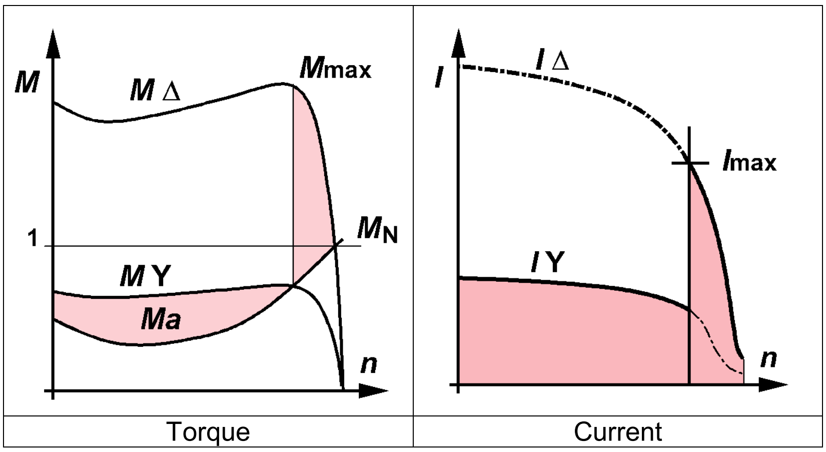


Fig. 13.8.1
Peak values of torque M_{max} and current I_{max} after switching over from Y to Δ if starting against heavy load

However, much more serious are occurrences as described by *Bunzel* in a detailed and demanding mathematical analyses [3.14]:
In the change-over-phase of star-delta-started cage induction motors very high current and torque peaks are generated depending on the phase relationship of the ***residual magnetic field*** and the restarting rotating field. Transmission components such as couplings can be damaged if the motor is loaded by a machine with high inertias. Typically the backside of the key will suffer – indicating that the damage is caused by a negative torque peak. A computer aided calculation resulted in negative torque peaks up to 15 times of the rated torque (Fig. 13.8.2).

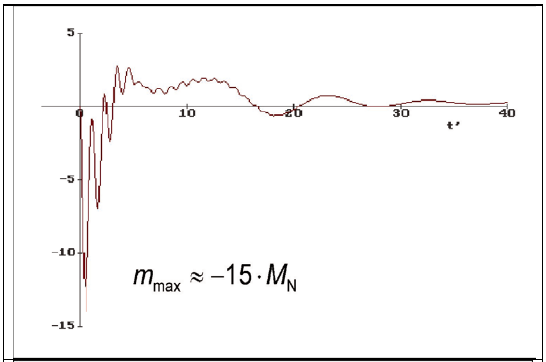


Fig. 13.8.2
Simulation of the torque generated at star-delta-starting with a 5 ms delay when switching over, negative torque peak nearly 15 times rated torque

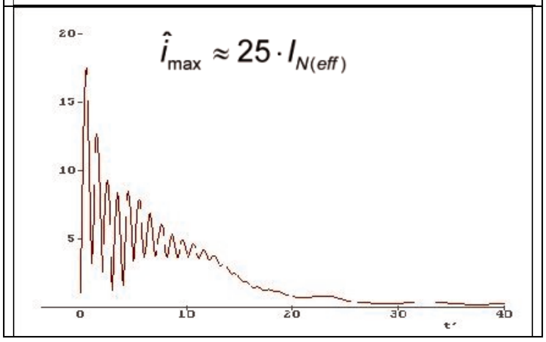


Fig. 13.8.3
Simulation of the current drawn at star-delta-starting with a 5 ms delay when switching over,
current peak nearly 25 times rated RMS current

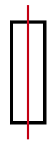
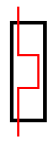
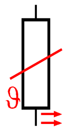
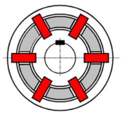
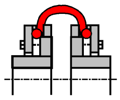
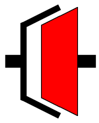
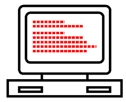
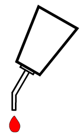
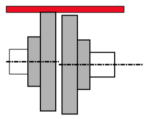
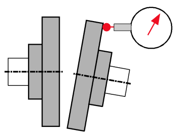
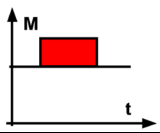
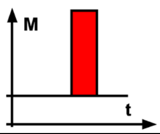
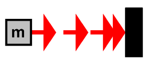
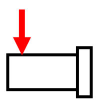
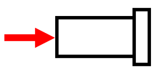
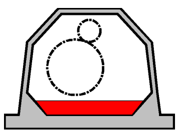
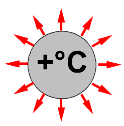
Source of pictures 13.8.2 und 13.8.3:
Dr. Bunzel, VEM motors

These considerations indicate that Star-Delta-Starting in many applications cannot meet the expectations put into a »soft-starting method«.

14 Provisions for protecting mechanical components

Table 14.1 provides a schematic representation of a few common types of mechanical overload and forms of protection.

Table 14.1 Protective effect of common protective elements for mechanical overload

Type of overload	**Protective element**							
								
	□	□	□	▼	■	□	□	□
	□	□	□	▼	■	□	□	□
	□	▼	▼	□	□	□	▼	□
	□	□	□	□	▼	■	□	□
	□	□	□	□	▼	■	□	□
	□	□	□	□	□	□	■	□
	□	□	□	□	□	□	■	□
	□	□	□	□	□	□	□	■
	□	□	■	□	□	□	□	▼
	□	□	□	□	□	□	□	■

□ No protection
▼ Partial protection
■ Full protection

Table 14.2 Key to the protective elements in Table 14.1

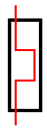
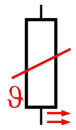
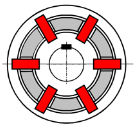
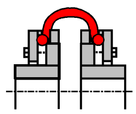
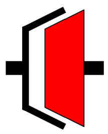
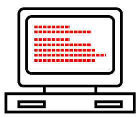
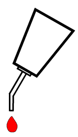
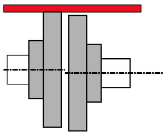
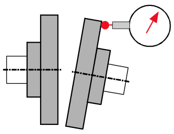
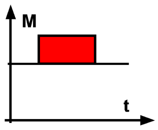
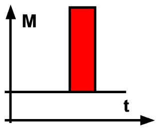
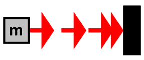
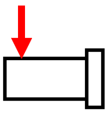
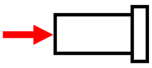
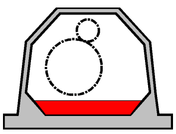
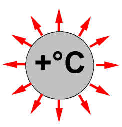
Symbol	Explanation
	Delayed-action fuse Rated value (1.6 to 2.5)·I_N
	Current-dependent delayed thermal overcurrent relay (bimetal relay = motor protecting switch) Setting current $I_E = I_N$
	TMS thermal motor protection (thermistor circuit-breaker) NAT in accordance with section 6.2.6 Response time $T_K < 6$ s
	Coupling with relatively high torsional stiffness, e.g. claw coupling, bolted coupling
	Coupling with relatively high elastic torsion, e.g. with shaft tyres, springs
	Slip clutch, centrifugal clutch, hydraulic clutch, shear pin, chain wheel with slip hub, shock absorber, resilient buffer; chain wheel with slip hub
	Correct planning
	Appropriate and timely lubrication

Table 14.3 Explanations on the types of overload in Table 14.1

Symbol	Explanation	See section
	Shaft offset (misalignment)	7.3
	Angular offset (misalignment)	7.3
	Long-term overloading e.g. $M \geq 1.2 \cdot M_N$	11, 12
	Short-term torque shock, e.g. $M \geq 2 \cdot M_N$	13
	Locking	13
	Excessive radial force	8.7, 11.3
	Excessive axial force	11.4
	Inadequate lubricant (quality or quantity)	10
	Long-term excessive ambient temperature ≥ 30 °C	4.2
	Ambient temperature too low when starting ≤ –20 °C	4.2.7

15 Provisions for protecting gear units and motors

Damage to the bearings on electric motors and to the gear unit on geared motors forms a large proportion of repair tasks in the maintenance of electrical machinery.
The main reasons for this are as follows: while there are well-established and relatively cheap devices available for protecting the winding against thermal overload, mechanical components are supplied without protection against shock loads, which have not been checked in any case (Fig. 15).
Incorrect or omitted lubrication is another major reason.

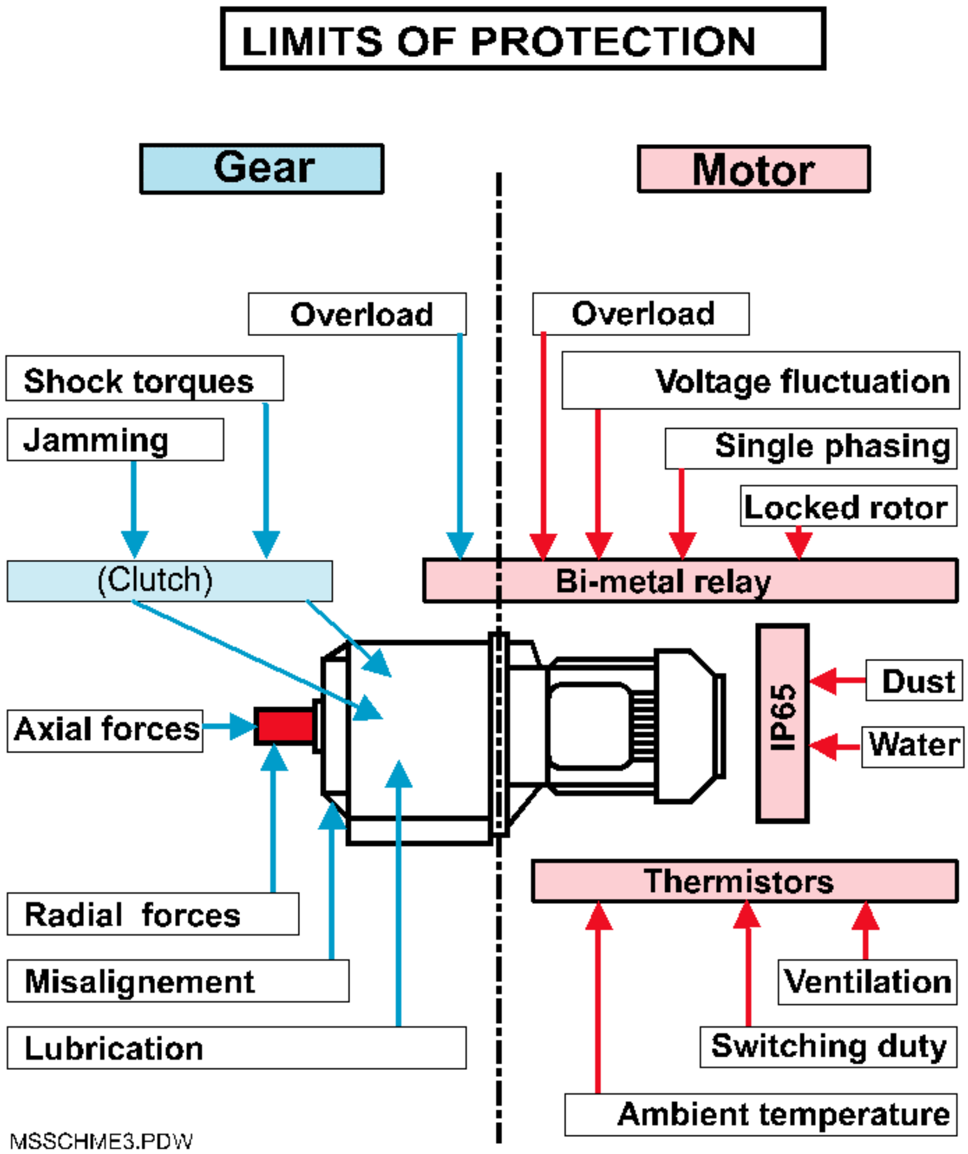


Fig. 15 Diagram of provisions for protecting gear units and motors
Reason for the relatively high proportion of mechanical damage out of the total number of repair operations

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selection and erection of electrical equipment; clause 51: Common rules

1.3 DIN VDE 0100-737 / VDE 0100 Part 737
Erection of power installations with nominal voltages up to 1000 V;
humid and wet areas and locations; outdoor installations

1.4 IEC 60721 Part 2-1
Classification of environmental conditions; environmental conditions appearing in nature; temperature and humidity

1.5 DIN IEC 60721 Part 2-2
Classification of environmental conditions; environmental conditions appearing in nature; precipitation and wind

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17 Index of keywords

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