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Appendix III: Generally used Abbreviations

ASIC	Application-specific IC	PLC	Programmable logic controller
CSI	Current Source Inverter	r	Radius
d	Distance	R_{FE}	Counter-resistance
DDC	Direct Digital Control	s	Slip
f	Frequency	S	Apparent power
F	Force	SFAVM	Stator Flux-orientated Asynchronous Vector Modulation
g	Force of gravity		
HP	Horse Power	S_M	Apparent power (motor)
I_1	Stator current		
I_B	Reactive current/flux-generating current	t_{acc}	Acceleration time
		t_{dec}	Deceleration time
I_L	Rotor current	t_{off}	Time transistor inactive
I_M, I_S	Motor current (apparent current)		
		t_{on}	Time transistor active
I_N	Rated current	T	Torque
I_W	Torque-generating current/active current	T_a	Starting torque
		T_{acc}	Acceleration torque
I_φ	Magnetising current	T_{dec}	Braking torque
IC	Integrated switching circuits	T_k	Break-down torque
		T_N	Rated torque
J	Moment of inertia	U	Voltage
L	Inductance	$\underline{U}_q$	Induction voltage
n	Speed	$\underline{U}_S$	Voltage drop (stator)
n_n	Rated speed	VVC	Voltage Vector Control
n_o	Synchronous speed	W	Work
n_s	Slip speed	WK^2	Flywheel effect
p	Number of pole pairs	X_h	Counter-reactance
P	Power/active power	X_L	Reactance (rotor)
P_1	(Electrical) input power	F	main flux, stator flux
		Φ	main flux, stator flux
P_2	(Mechanical) output power	Φ_L	Rotor flux
		η	Motor efficiency
P_V	Power loss	ω	Angular speed

Appendix II: General AC theory

AC stands for Alternating Current and is symbolised by "~". This current alternates both its size (amplitude) and its direction.

Current in one direction

Current in the other direction
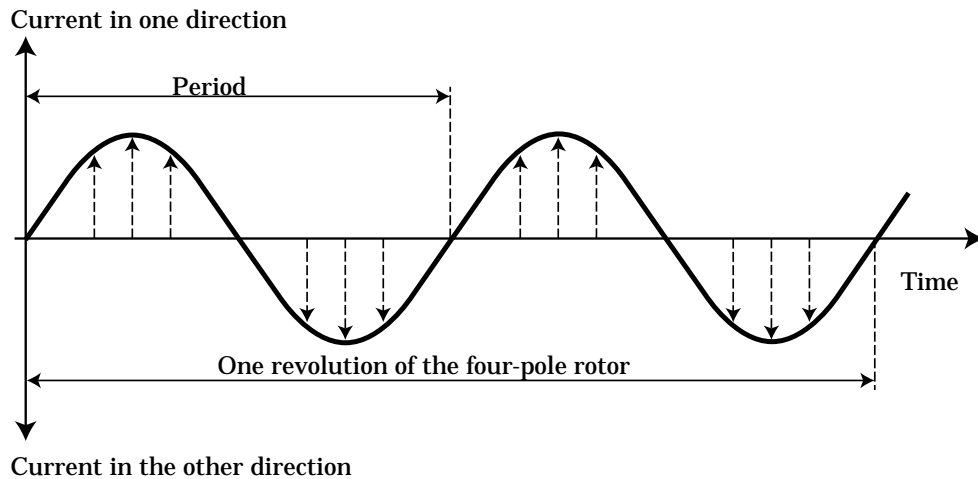
Fig. AII.01   Different values for alternating current

The figure for periods per second is called frequency and is stated in Hertz. 1 Hz = one period per second. The duration of one period is the period time, which is calculated as follows $T = \dfrac{1}{f}$

At a frequency of 50 Hz, the period time is 0.02 seconds.

As opposed to DC voltage and direct current, which are characterised by having just one direction, AC voltage and alternating current are characterised by having more than one direction.
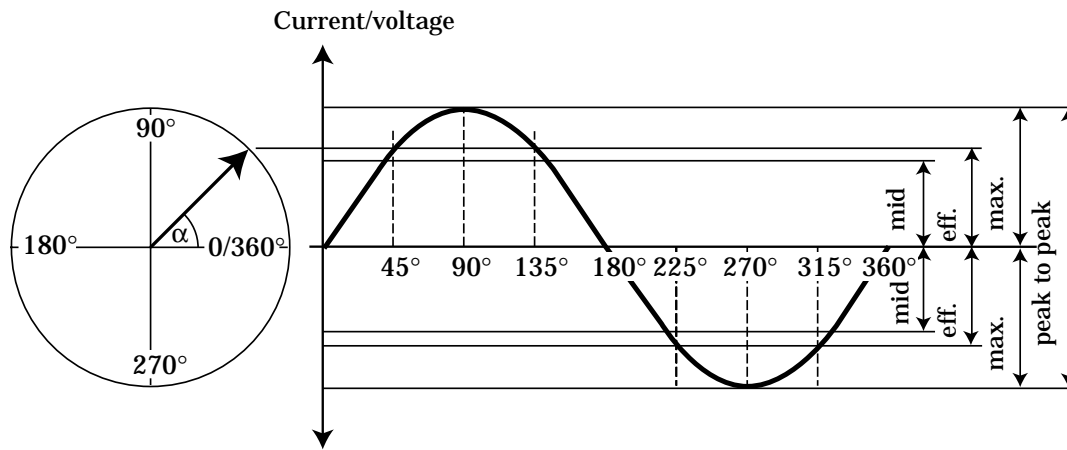
Fig. AII.02   Different values of AC voltage
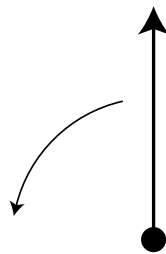
Fig. AII.03   The vector direction of rotation is anti-clockwise

Normally, the effective value is used. An alternating current of 1 A develops the same heat in a given resistor as a direct current of 1 A.

Vectors are very useful with alternating currents and AC voltages. They clarify the connection between current, voltage and time. A vector is characterised by its length and direction of rotation. The positive direction of rotation is anti-clockwise.

When a vector turns a full circle from its starting point, the vector peak runs 360°.
The time of one revolution is identical to the period time of the sinusoidal curve. The vector speed per second is stated as angular speed and with the Greek letter ω. $\omega = 2 \times \pi \times f$.

There are three types of AC loads.

If the load consists of coils with an iron core as in motors, the load is mainly inductive. In this case, the current is delayed in time in relation to the voltage.

The load can be capacitive. Here the current is ahead of the voltage in time. In the case of a purely resistive load, there is no displacement between current and voltage.

The displacement between voltage and current is called the angle of phase difference and the Greek letter Φ.

Multiplying the current and voltage values which belong together results in a power characteristic for the three types of load.
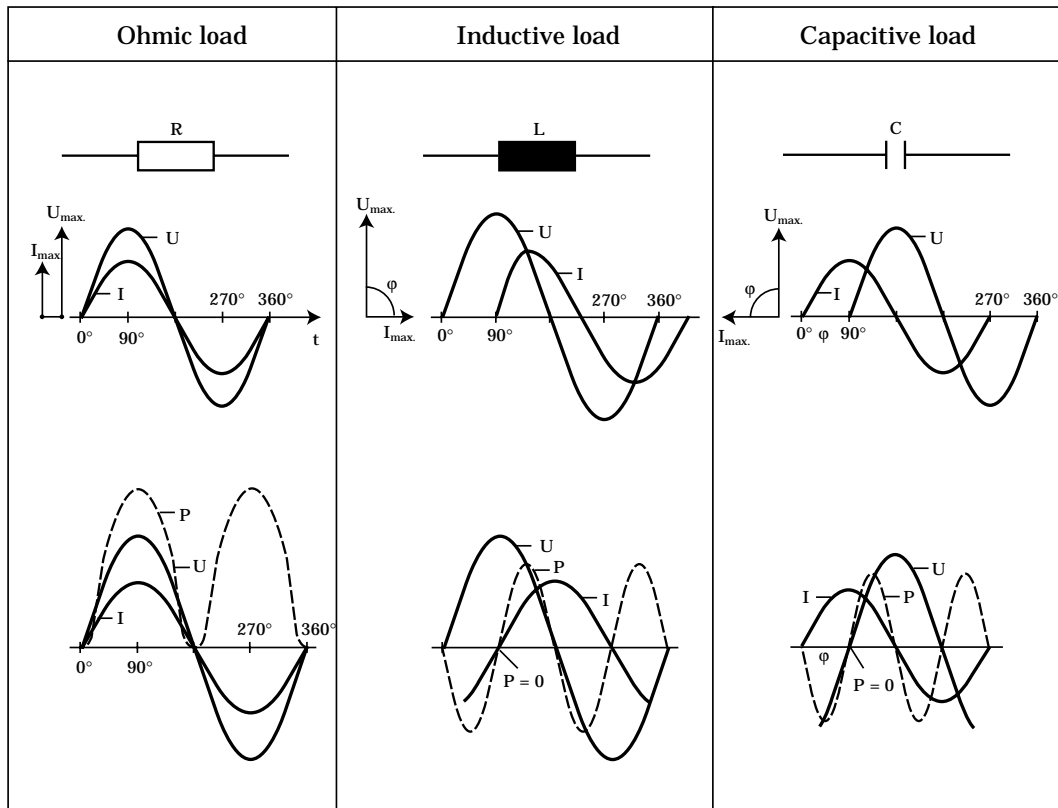
Fig. AII.04   Current, voltage and power under load

The "pure" types of load are only theoretical values when AC circuits are described. A load is either inductive or capacitive.

Power factor

The power factor λ is defined as the ratio between the active power and the apparent power.

Often, this factor is also called cos φ; however, cos φ has only been defined for sinusoidal currents and voltages.

In the case of non-linear loads such as the frequency converter, the load current is not sinusoidal. Consequently, a distinction must be made between cos φ and the power factor.

$$\lambda = \frac{P}{I \times U} = \frac{I_W}{I}$$

P is the active power, I_W is the active current, I and U are effective values.

φ is the phase difference between current and voltage. If there is a purely sinusoidal current and voltage, cos φ thus corresponds to the relation between active power and apparent power.

	Formula sign		In general	Unit
Power	P	=	$U \times I \times \cos \varphi = S \cos \varphi$	W or kW
	Q	=	$U \times I \times \sin \varphi = S \sin \varphi$	VAr or kVAr
	S	=	$U \times I = \dfrac{P}{\cos \varphi} = \dfrac{Q}{\sin \varphi}$	VA or kVA
Voltage	U	=	$\dfrac{P}{I \times \cos \varphi} = \dfrac{Q}{I \times \sin \varphi} = \dfrac{S}{I}$	V
Current	I_S	=	$\dfrac{P}{U \times \cos \varphi} = \dfrac{Q}{U \times \sin \varphi} = \dfrac{S}{U}$	A
	I_W	=	$\dfrac{P}{U} = \dfrac{S \times \cos \varphi}{U}$	A
	I_B	=	$\dfrac{Q}{I} = \dfrac{S \times \sin \varphi}{I}$	A
Phase displacement	cos φ	=	$\dfrac{P}{U \times I} = \dfrac{P}{S}$	no unit
	sin φ	=	$\dfrac{Q}{U \times I} = \dfrac{Q}{S}$	no unit

Fig. AII.05

3-phase AC current

In a 3-phase voltage system, the voltages are displaced by 120° in relation to each other. The three phases are normally depicted in the same system of co-ordinates.
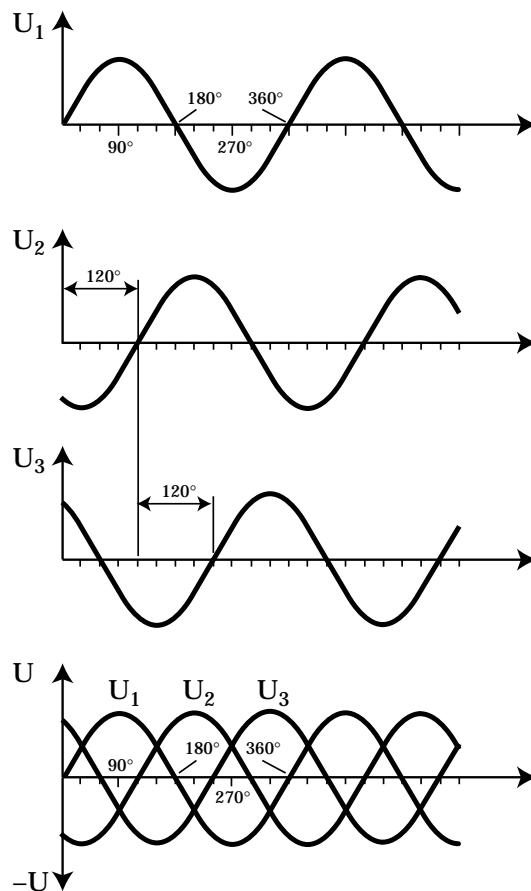
Fig.AII.06   A 3-phase AC voltage consists of three individual AC voltages displaced in time

The voltage between a phase conductor and the zero conductor is called phase voltage U_f and the voltage between two phases is called mains voltage U_N.

The ratio between U_N and U_f is $\sqrt{3}$.

Star or delta connection

When a three-phase mains supply is subjected to a motor load, the motor winding are connected in star or delta formation.
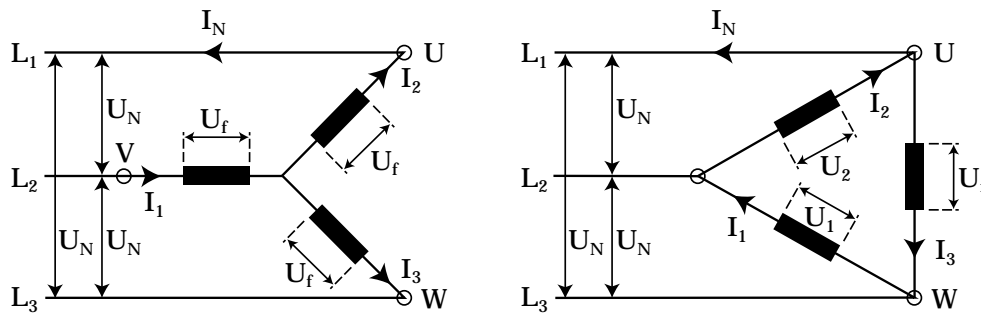
Fig. AII.07   Mains and phase values in star or delta connection

In star connection, each phase is connected to one end of the motor windings, while the other ends are short-circuited (star point). The voltage across the individual windings is

$$U_f = U_f = U_f = U_f = \frac{U_N}{\sqrt{3}}$$

For the currents, the following applies: $I_1 = I_2 = I_3 = I_N$

In delta connection, the motor windings are connected in series. Each connection point is connected to a phase.

The voltage across the individual windings is

$$U_N = U_1 = U_2 = U_3$$

For the currents, the following applies $I_1 = I_2 = I_3 = \dfrac{I_N}{\sqrt{3}}$

Appendix I: General mechanical theory

Straight-line motion

With respect to straight-line motion, a body lies still or maintains its straight-line motion until a force impacts.

The force, F, can be described as a product of the mass of the body and the change per time unit of the speed of the body. The speed change per time used is also known as acceleration, a.

$$F = m \times a$$

Mass: "m" measuring unit: [kg]

Acceleration: »a« measuring unit: $\left[\dfrac{m}{s^2}\right]$

Force: "F" measuring unit [N]

To maintain a constant motion a body must be continually impacted by a force, otherwise the forces which work against the direction of motion, such as friction and gravity, will cause it to slow and stop.

Rotating motion

In the case of a rotary motion, a body can be made to rotate or change its direction of rotation if it is impacted by a torque around its mass centre. Like the force, the torque can be stated by way of its effect. Torque is a product of the moment of inertia of the body and the speed change of that body per time unit, i.e. the angular acceleration, α.

$$T = F \times r$$
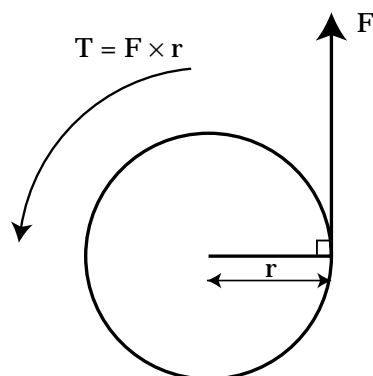
Fig. AI.01

$$T = J \times \alpha \qquad \omega = \frac{2\pi n}{60}; \text{ n Measured in [revolutions min}^{-1}]$$

Angle speed: ω measuring unit: $\left[\dfrac{\text{angle change}}{s} \right]$

Angle acceleration: $\alpha = \dfrac{d\omega}{dt}$; measuring unit $\left[\dfrac{\text{angle change}}{s^2} \right]$

Moment of inertia: J; measuring unit: [kg m^2]

Like the mass, the moment of inertia dampens acceleration. The moment of inertia depends on the body mass and the position in space in relation to the rotation shaft.

Solid cylinder:

$$J = \frac{m \times r^2}{2}$$

$$J = \frac{m \times r^2}{4} + \frac{m \times l^2}{12}$$

Hollow cylinder:

$$J = \frac{m}{2} \times (r_1^2 + r_2^2)$$

Solid ball:

$$J = \frac{2 \times m \times r^2}{5}$$
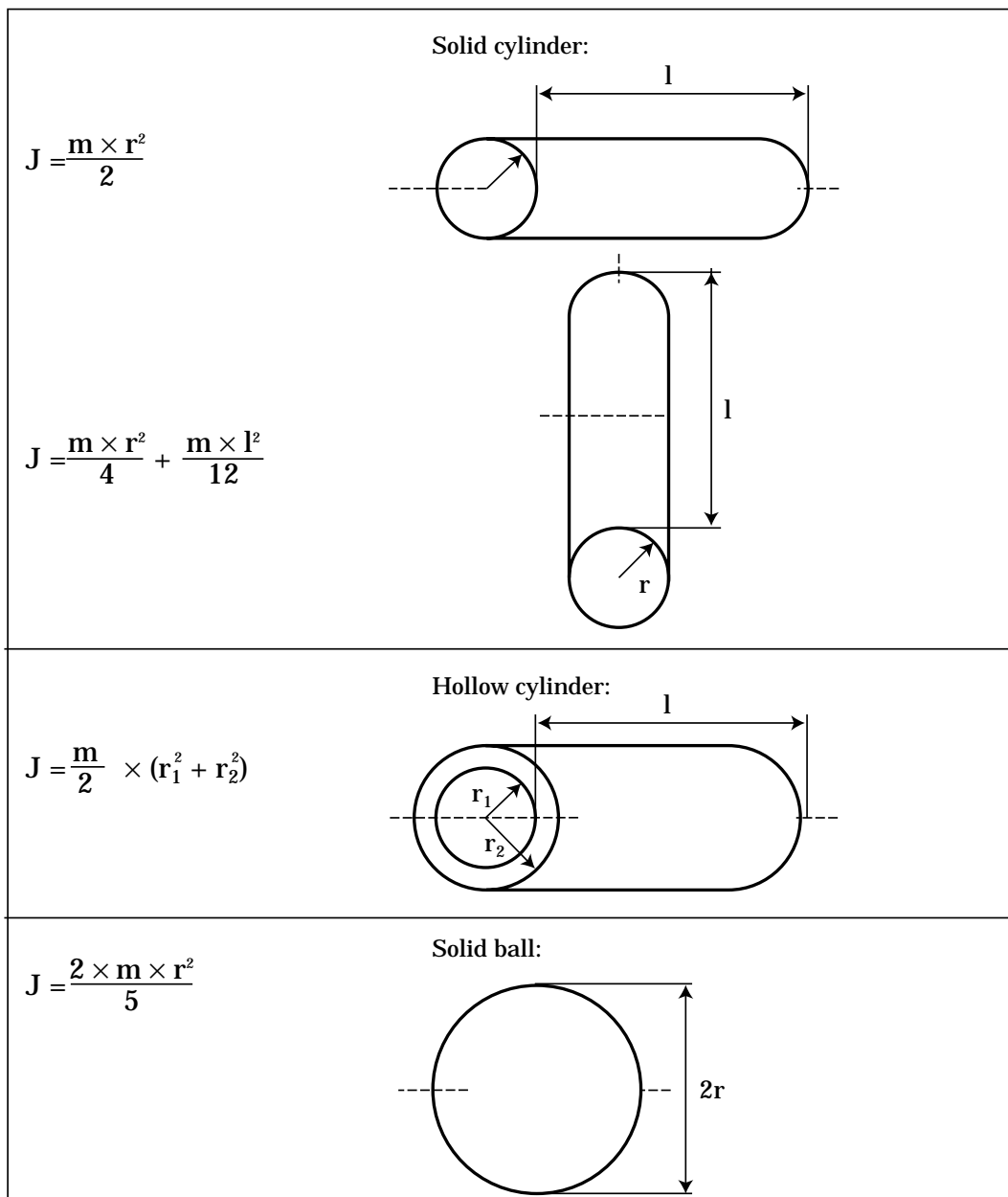
Fig. AI.02   Calculation of different moments of inertia

When the torque and acceleration of a system are to be calculated, it is preferable to place all masses and inertia in one moment of inertia on the motor shaft.

$$J = J_1 + J_2 \times \left(\frac{\omega_2}{\omega_1}\right)^2 + J_3 \times \left(\frac{\omega_3}{\omega_1}\right)^2 + \ldots$$

J_1:   own moment of intertia of the motor, etc.

J_2, J_3:   the invidual moments of invertia of the system

ω_1:   angular speed of motor, etc.

ω_2, ω_3:   angular speed of the individual rotating

Work and power

The work carried out by a motor in straight-line movement can be calculated as the product of the force of the direction of movement "F" and the distance "s" which the body is moved.

$W = F \times s$ Lengthe of movement: s   measuring unit: [m]
Work: W   measuring unit: $[W \times s]$

In rotating movements, the work is calculated as a product of the torque T and the angular movement (φ).
One revolution = $2 \times \pi$ [rad].

$W = T \times \varphi$ Angular movement: φ measuring unit: angle change
1 revolution = $2 \times \pi$ [rad]

The work carried out by a conveyor system increases with time. There is thus no maximum value and there is no figure to be used in calculations.

The power, P, is the work per time unit and this does have a maximum value.
In the case of straight-line movement, the power is calculated as the product of the force in the direction of movement and the length of movement per time unit, the speed "v".

$P = F \times V$ measuring unit: [W]

With respect to rotating movement, it also applies that the power can be calculated as a product of the torque and the length of movement per time unit, the angular speed ω.

$P = T \times \omega$ measuring unit: [W]

4. Protection and safety

Based on the regulations that apply to a given installation, it may be necessary to place an emergency switch near the motor. It is important to place the switch in the motor cable in such a way that the motor and frequency converter are not damaged – and preferably independent of the switching frequency.

Galvanic isolation is required between the control part and the power part of the frequency converter. Otherwise the control cables could have the same voltage in relation to earth as the mains supply and touching the control cables could be fatal or, less seriously, the equipment could be damaged.

European standard EN 50178 describes the guidelines for galvanic isolation. The type of protection provided for frequency converters offers protection against injuries from touching.
IP 20 provides total enclosure of live parts. IP 54 is a splash-proof enclosure.

Additionally overheating could turn a frequency converter into a fire hazard. Consequently, an integral thermal sensor should be fitted to cut the voltage feed in the case of cooling failure.

A motor connected to a frequency converter may under certain circumstances, restart without warning. This could happen if for example, the time function elements are activated in the frequency converter or temperature limits are monitored.

Extra protection
Extra protection helps to avoid dangerous voltages on the outside of the housing. For frequency converters, extra protection is always required. The mode of protection must be assessed on a case-to-case basis, depending on the local conditions and regulations. The different types of protection are zeroing, earthing and protective relays.

Reset to zero (TN system)

A protective wire can be fitted between the earth terminal and the zero conductor in the installation supply cable. This type of extra protection is often used in industrial networks and housing installations that are supplied with earth wire. If the installation has not been zeroed whether this method can be used will depend on the connection conditions and it may be necessary to talk to the frequency converter supplier.
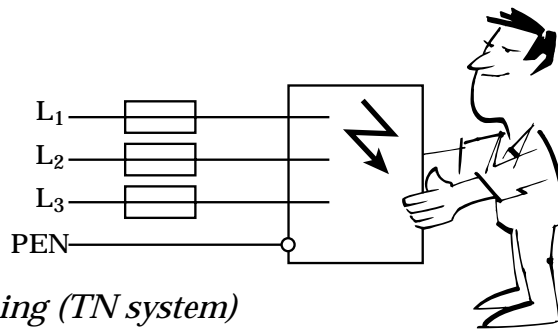
Fig. 4.01   Zeroing (TN system)

Earthing (TT system)

A protective wire can also be fitted between the earthing terminal and the equipotential bar. However, to use this method the impedance of the equipotential point must be sufficiently low. Based on the interference reduction components, the frequency converter has a leakage current, which is why the earthing should be of low impedance. EN 50178/5.3.2.1 sets up the following requirements:

For a leakage current greater than 3.5 mA, the cross-section of the protective wire must be at least 10 mm^2, or the unit must be earthed by means of two separate protective wires, which have to fulfill the requirements of IEC 364-5-543. This is often termed re-inforced earthing.
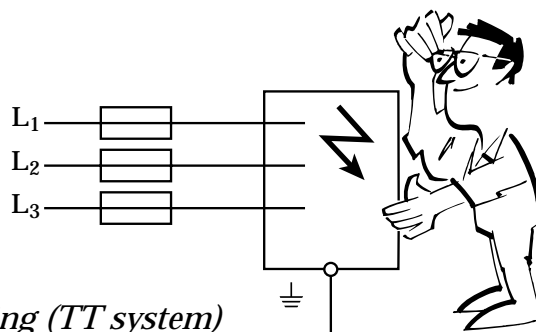
Fig. 4.02   Zeroing (TT system)

Protective relays

There are two types of protective relays for extra protection. One type uses a fault voltage relay, the other a fault current relay.

Extra protection in the form of a fault voltage relay (FV relay) is possible in most installations. Protection is obtained by connecting the relay coil via a protective wire between the frequency converter earth terminal and the earth potential. A faulty voltage releases the relay and makes the frequency converter voltage-free.

FV relays can be used with good results where zeroing is not allowed or where the ground does not allow earthing. Whether such relays are permitted depends on the regulations from the electricity supply companies.

Protection of frequency converters using a residual current detector (RCD) is permitted under certain conditions.
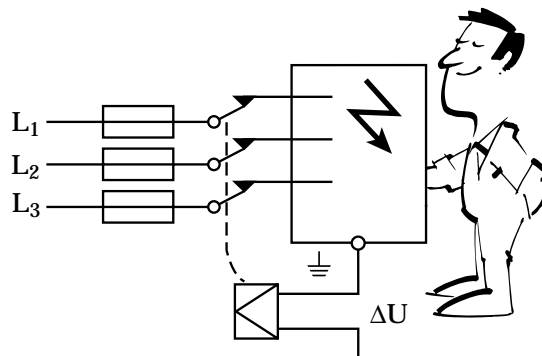
Fig. 4.03   Fault voltage relays

RCD devices put all the supply cables to the frequency converter through a summation current transformer which measures the sum of the currents through the cables to ensure it is zero. Otherwise a current is automatically induced in the secondary winding of the transformer which cuts out the relay and removes power to the frequency converter. In traditional RCD's the induction principle was used, which works exclusively with AC voltage. According to EN 50178, frequency converters with 6- pulse input bridge rectifiers may allow a smooth direct current to flow in case of a fault. Best practice is to test if DC can be measured at the frequency converter input.

According to EN 50178 smooth d.c. currents can be generated, if failures occur in frequency converters with 3-phase rectifiers. An RCD relay can be used as extra protection. This must be a type B relay, as described in IEC 755.
In practice this means that the relay must be marked with the following symbol: ⎓⎓⎓

If fault current protective switches are used that are not DC-compatible, an isolating transformer placed before the frequency converter is able to prevent this fault current.
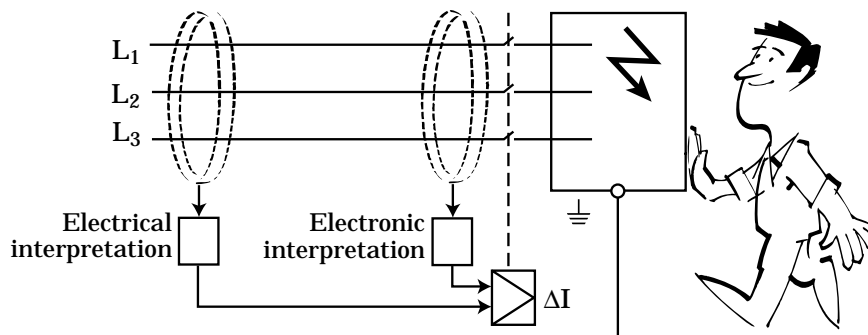
Fig. 4.04   All-current sensitive fault current relay

Leakage currents are to some extent produced by radio interference filter components. Individual radio interference filters normally generate a leakage current of only a few mA which does not lead to a release. If, however, several or very large filters are used, this may cause a RCD relay to trip.
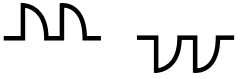
$\sim$	Alternating fault currents
⌒⌒ ⌄⌄	Pulsating DCs (pos. and neg. half-wave) half-wave current
⌓⌓ ⌄⌄	Sloping half-wave currents Angle of slope 90° el. 135° el.
⌒⌒	Half-wave current with overlay of smooth fault DCs of 6 mA
= = =	Smooth fault DCs

Fig. 4.05   Curvature and characteristics of fault currents

Electromagnetic compatibility

Electromagnetic interferences are unwanted electrical pheno-mena that stem from the unit or affect the unit in an unwanted way.

Electromagnetic phenomena may arise from nature or be gen-erated by man.

Among the electromagnetic interferences that appear naturally are atmospheric interferences, such as lightning. Another phe-nomenon is the magnetic field that surrounds the entire globe and protects us from the energy-intensive radiation that comes from space. Whilst atmospheric interference cannot be avoided its influence on electrical units and installations can be limited.

Unnatural interferences, not caused by nature, are considered artificial electromagnetic phenomena and occur wherever elec-trical energy is used. This interference can disperse through air or through the electrical wiring. Examples include interference from light switches or ignition systems being experienced on radio or TV. Additionally if there is a short voltage drop-out, clocks may stand still or PCs may not work properly.

Mains supply interference

Corona

Radioactivity

Micro-waves

Magnetic fields

Biological effects

EMC

Resistance to interference

Lightning protection

Radio interference

Touch injury protection

Electrostatics

Elect. corrosion
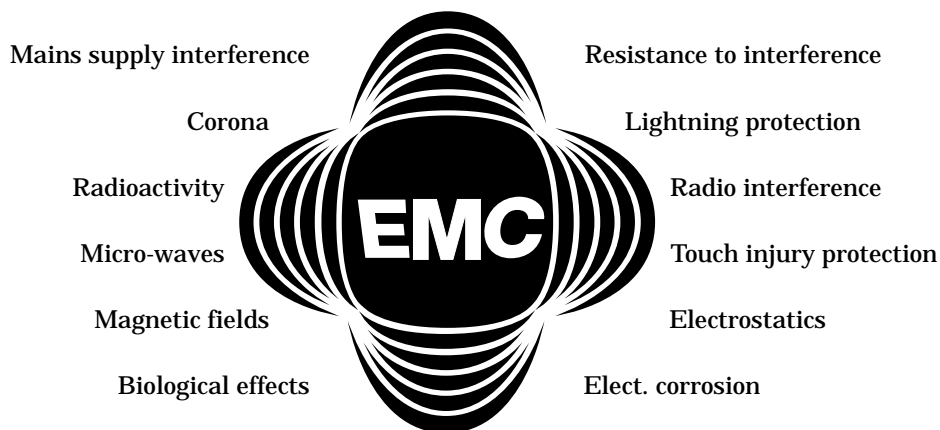
Fig. 4.06   Electromagnetic phenomena

Electrostatic discharge can also lead to faults in electronic switches and even to fire hazards and there are a number of mutual effects on people, plants and animals.

The international term for radio interference is EMC (or Elec-tromagnetic Compatibility). This is described as the ability of a

unit to resist electrical interference and not to emit interference to its surroundings.

In Europe, an EMC directive was adopted in 1989 and today Europe's EMC standards are divided into three groups:

Basic Standard

These standards are phenomenon-oriented. They describe the set-up of the required testing equipment and measuring procedure.

Generic Standard

These standards are environmentally oriented. They distinguish between residential areas, office areas, light industry, manufacturing industry and special applications.

Product Standard

These standards relate to the specific requirements of given product families with respect to measuring procedure and assessment. Exact test levels and limit values are prescribed. These standards have priority over the generic standards.

If an electrical or electronic unit adheres to the European legislation, it must be submitted to, and substantiated by, the authorities at a specified time. This is done in the form of an EU Declaration of Compliance and by CE labelling. The EU Declaration of Compliance is issued as verification for a series of units, and the CE label is placed on the unit, packing and operating instructions. The CE label is an authority symbol addressed to the relevant European authorities and confirming that the relevant rules and regulations have been complied with.

Products that require a CE label in accordance with the EMC directive must now carry this label.

CE

Fig. 4.07   EU sign of compliance

If an electrical unit operates in the voltage range from 50 to 1000 V AC or between 75 and 1500 V DC, the low-voltage directive must also be complied with. This directive came into force in 1997 and refers to dangers that may arise from electrical machinery for people, domestic animals or objects.

	1992	1993	1994	1995	1996	1997
EMC 89/336/EWG						
Low-voltage 72/23/EWG						
Machines 89/393/EWG						
CE labelling 93/68/EWG						
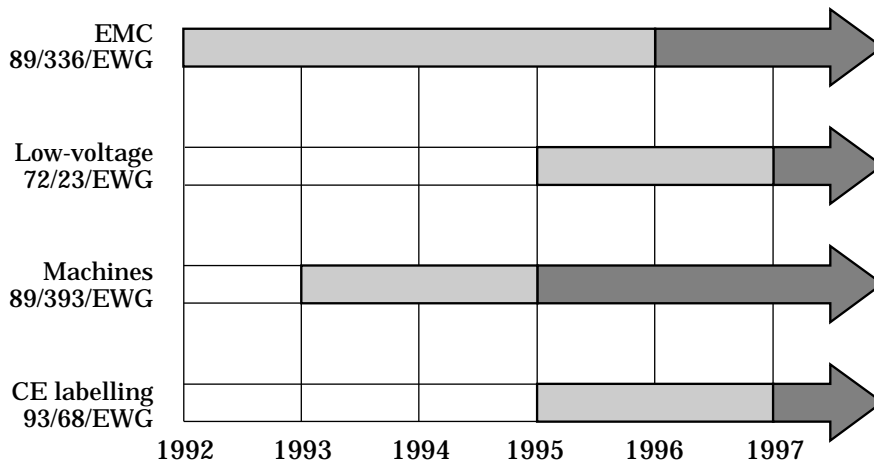
Fig. 4.08   Transition deadlines for CE labelling

Dispersal of interference

Emission (interference transmission) is the electromagnetic energy (or amount of interference) coming from a unit and immunity is the ability of a unit to resist or suppress the interference.

The interference coming from a frequency converter is mains supply interference in the low-frequency range, which is dispersed through the cable network as hard-wired interference, and interference radiated into the air at high-frequency (10 kHz to GHz).

Coupling

Electrical circuits can be coupled using galvanic, capacitative or inductive coupling. Galvanic coupling may occur when two electrical circuits share a common electrical impedance.
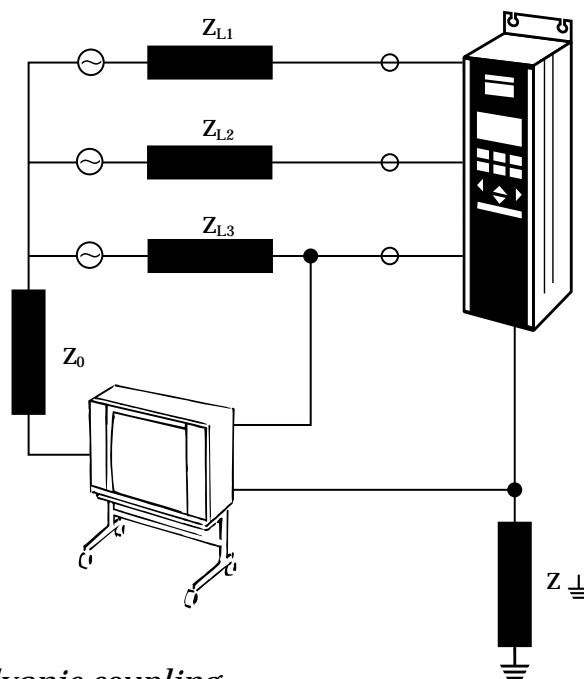
Fig. 4.09   Galvanic coupling

Frequency converters and other electric units operating in the system are connected to each other by conductors and have the same earthing potential. Depending on the impedance relation, this coupling leads to an interference voltage at a unit across the two shared impedances Z_{L3} and Z_0.

Capacitive coupling occurs when two electrical circuits have a common earthing reference. Typically this occurs where a motor cable has been laid too close to other cables. The capacitive interference current depends on the frequency of the motor cable, the related voltage and the distance to other cables. The relatively high switching frequency of today's frequency converters, with which the output voltage is generated, results in a low capacitive resistance in the motor cable and thus causes capacitive interference currents.
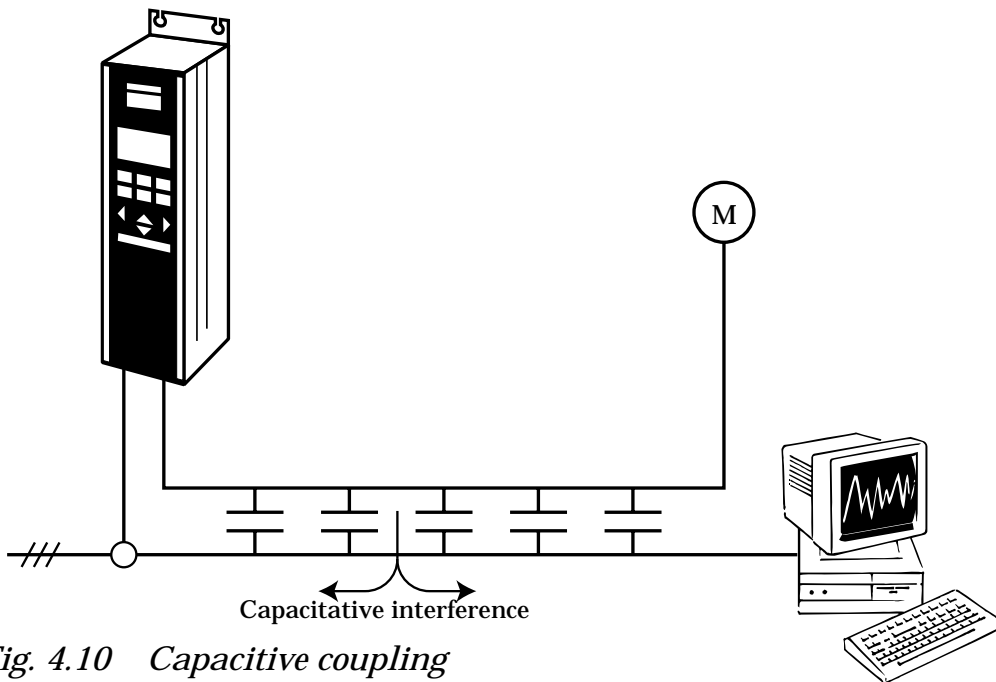
Fig. 4.10   Capacitive coupling
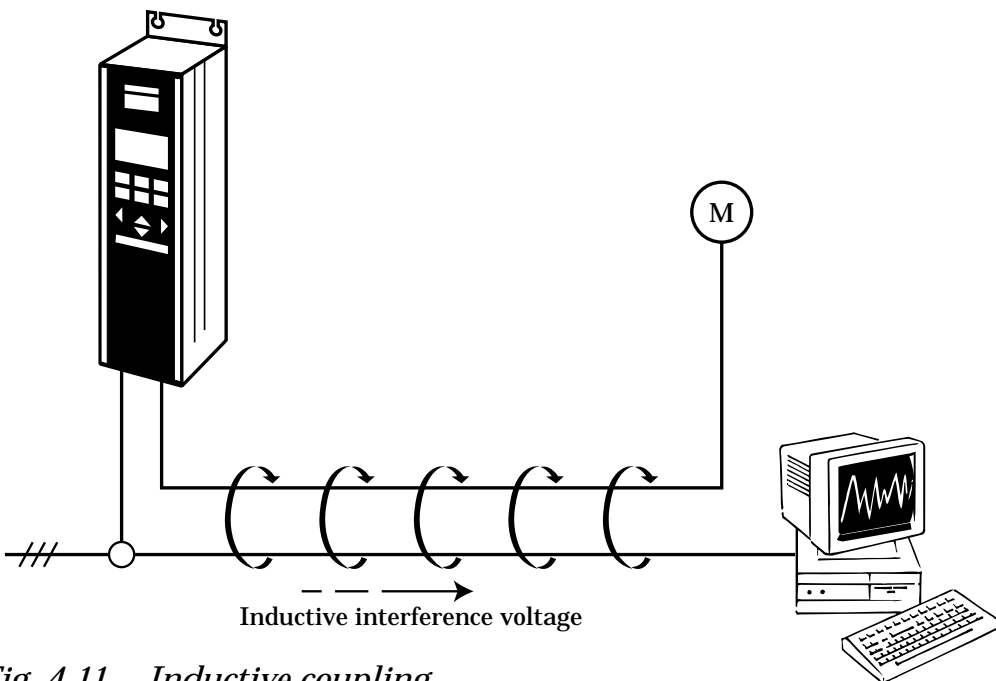
Fig. 4.11   Inductive coupling

Inductive coupling occurs when the magnetic field around a current-conducting wire induces a voltage in another wire. The induced AC voltage depends on the strength of the magnetic field, as well as on the strength of the current in the motor cable, the frequency and the distance between the cables.

Hard-wired dispersal

Electrical noise can spread through the cables of the mains supply. Higher frequencies are superimposed on the 50 Hz sinusoidal curve of the supply voltage. A distortion of the pure sinusoidal curve occurs.

Mains supply interference

Mains supply interference from electricity consuming units causes a distortion of the supply voltage. This distortion is created by high frequency components of the current drown by the input circuits of inverters and other semi-conductor products due to their non-linear nature. In other units connected to the same mains supply, interference courses an additional load. This is reflected in the form of higher current consumption and for acoustic handling in the units.
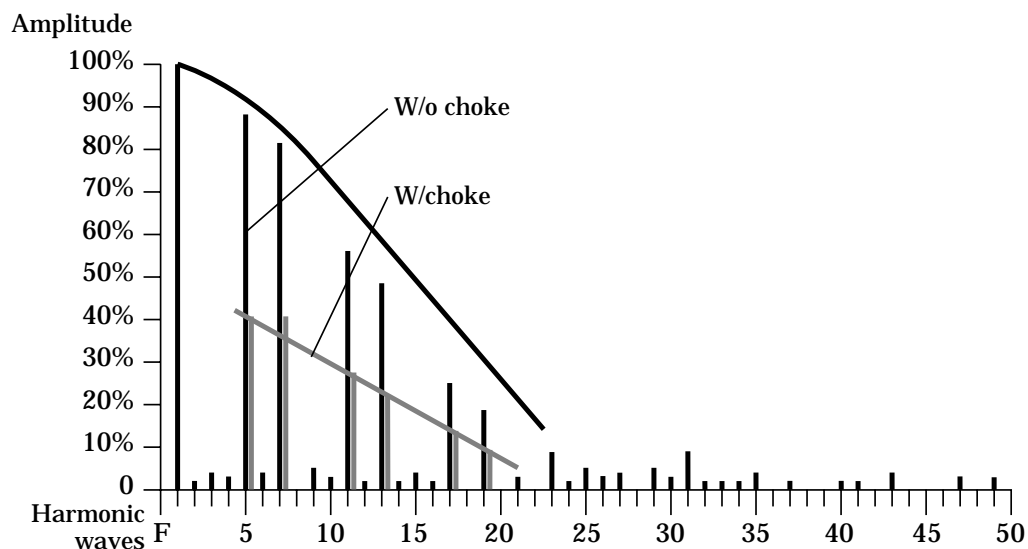
Fig. 4.12   Reduction of harmonic currents by incorporating DC link chokes in the VLT 5000

The rectifier of a frequency converter generates a pulsating DC voltage. The capacitor of the following DC voltage intermediate circuit is charged at each voltage peak. During this charging process, input currents with relatively high amplitude occur. Because of this pulse-shaped, non-sinusoidal load, the sinusoidal shape of the supply voltage is distorted and the degree of distortion depends on both the current load and the mains impedance.

The maximum permissible distortion is given in EN 61000-3-2 for public networks and in EN 61000-3-4 for public low voltage systems. The mains supply interference consists of the high-frequency parts in the form of so-called harmonics of the basic frequency of the supply voltage. The total harmonic content is termed Total Harmonic Distortion (THD).

$$\text{THD [\%]} = \frac{\sqrt{(U_3)^2 + (U_5)^2 + ... + (U_N)^2}}{U_1}$$

The maximum permissible size of the individual mains voltage harmonics is dictated in EN 61000-3-2, table 1. The mains supply interference can be reduced by limiting the amplitude of the pulse currents. In practice, chokes are integrated in the intermediate circuit or in the frequency converter input. Often, frequency converters are supplied without chokes. Chokes can be ordered separately and installed subsequently. The harmonic levels of the mains voltage with which a frequency converter can cope are stated in standard EN 60146-1-1 (general requirements for semi-conductor power converters).

Transients/over voltage

Transients – or brief over voltage peaks in the range of some thousand volts – can occur in the mains supply, both in industry and in the private house-holds.

They can be caused by heavy loads in the mains supply being switched on and off, or due to power factor compensation units. If lightning strikes directly in the supply cables, for example, there will be a high over voltage peak resulting in damage to installations up to 20 km away. In open-air installations, jumping of the isolators to other cables may occur.
Short-circuits and safety switch-offs of the mains supply also lead to transients. Through magnetic inductive couplings, cables laid out in parallel may also cause high voltage peaks.

The shape of these transients and the energy they contain are explained in EN 61000-4-1, and VDE 0160.
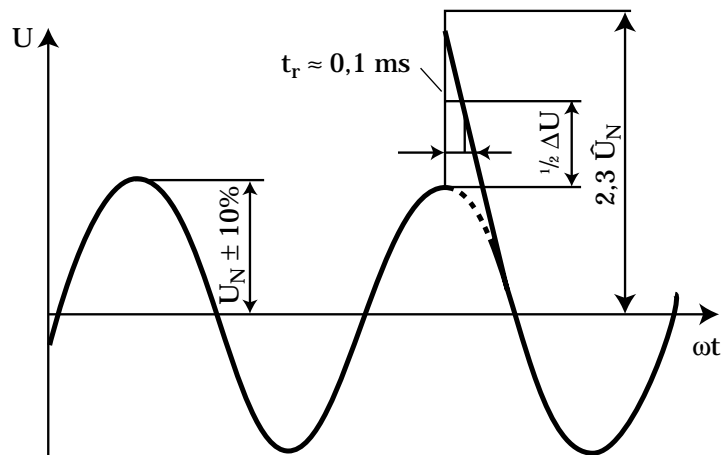
Fig. 4.13   Mains transients according to VDE 0160 from December 1990

Danfoss has chosen to follow the requirements of VDE 0160 (version 2) although it is no longer valid. The reason is that this stringent standard includes the rough conditions the frequency converters are often exposed to.

The harmful effects of transients and over voltages can be limited in a number of ways. To combat energy-intensive transients and over voltages, gas eliminators or spark gaps can be applied. In electronic units, voltage-dependent resistors (varistors) are often used to dampen the over voltages. In the signal range, protection may be ensured by means of a breakdown diode.
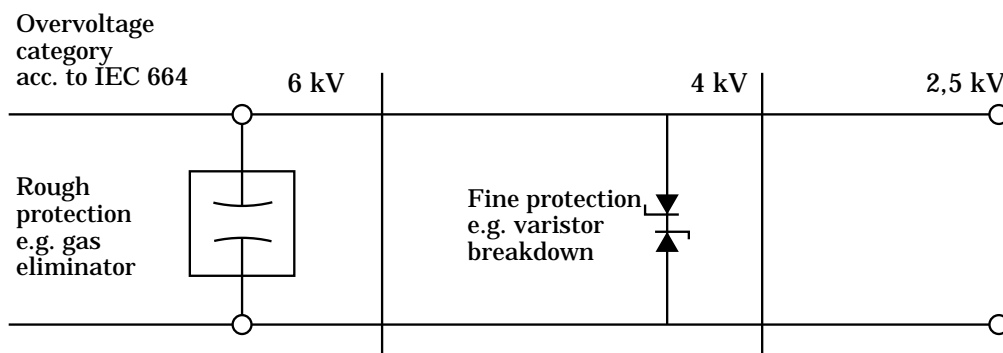
Fig. 4.14   Transient protection

Radio frequency interference

Every current and voltage that deviates from the pure sinusoidal form contains components with higher frequencies. The magnitude of these frequencies depends on the rate of change of the process.

When a contact mechanism closes or opens, the current change takes place very rapidly and a very steep current change is registered. This is also reflected in the voltage. On radio, this phenomenon can be heard as crackling noise. In this context, a single noise pulse is normally not considered to constitute interference. However, since the frequency converter semi-conductors are switched in the form of contact elements in the kHz range with steep switching flanks, permanent radio frequency interference is generated and radiated.
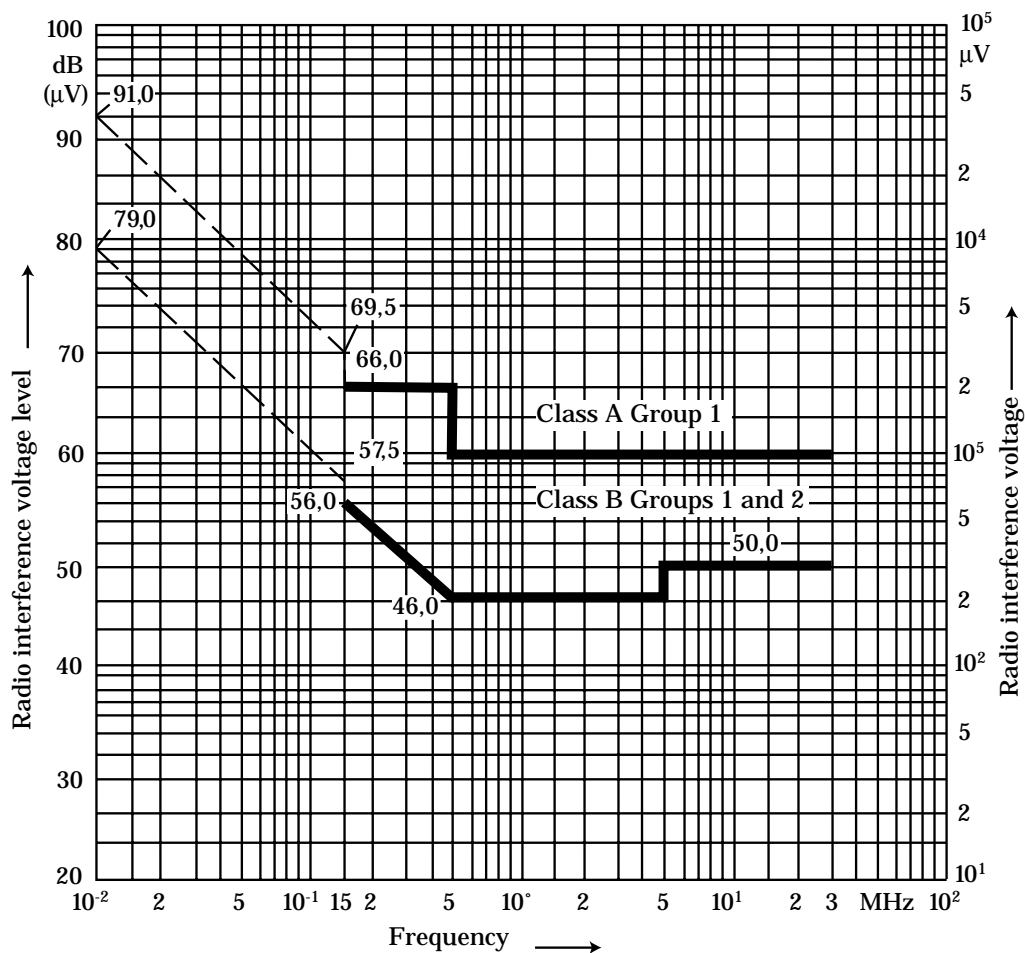
Fig. 4.15   Average radio interference threshold values to EN 55011

Radio frequency interference (RFI) is defined as electric oscillations with frequencies between 10 kHz and the GHz range.

The extent of this interference depends on a number of factors:
- the impedance of the mains supply
- the switching frequency of the inverter
- the mechanical build-up of the frequency converter
- the frequency of the output voltage to the motor
- the anti-interference measures taken
- the length and type of motor cable.

Radio frequency interference is emitted by conduction or radiation and limited by EN standards in Europe and IEC standards world-wide.

Limit values and measuring procedures for radio interference from industrial, scientific and medical high frequency units (ISM units), which until recently also included frequency converters, are covered by EN 55011. Limit values for emissions from electrical household appliances are covered by EN 55014. Now frequency converters are covered by the product standard EN 61800-3.

High-frequency mains conducted interference can only be reduced effectively using a filter which consists of coils and capacitors. Not all frequency converters come with a radio interference filter, in which case the filter must be fitted subsequently – class A filters for industry, class B filters for household appliances.
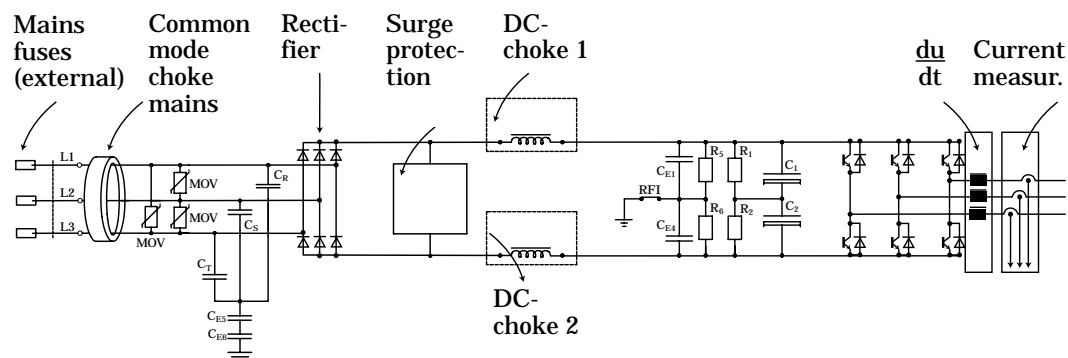
Fig. 4.16   Frequency converters and radio interference measures

On the cable from the frequency converter to the connected motor, radio interference can be limited using filters or screened/armoured cables. In this connection, the high switching frequency of inverter means:

• that the capacitors have to take up higher currents
• that the filter coils must be oversized.

Screened/armoured cables

Screened/armoured cables are often used to limit radio interference. The effect of the screen is stated in decibels (dB) as screen attenuation or coupling impedance.

The screen attenuation should be as high as possible (normally in a range of 30 dB), while the coupling impedance should be as low as possible.

For the screening against high-frequency interference to be truly effective, the screen should be earthed at both the frequency converter and motor ends and be continuous between both ends. In practice, if it is broken a high frequency, low impedance link should be made across this break. A good contact between screen and earth potential is important, as a poor connection reduces the screening effect and thus the attenuation of the interference. It must be considered that if earthing is made at several places, an equalising current will flow across the earth potential. Consequently, signal cables should only be earthed at one end. Since these signal cables work with very small signal sizes, connection to the screen would have a disturbing effect.

When a frequency converter is purchased and installed, it must be considered how and to what extent radio interference is to be

Cable clamp   Earth terminal   Cable gland

Good   Bad   Good

Fig. 4.17   EMC-correct installation of the screen

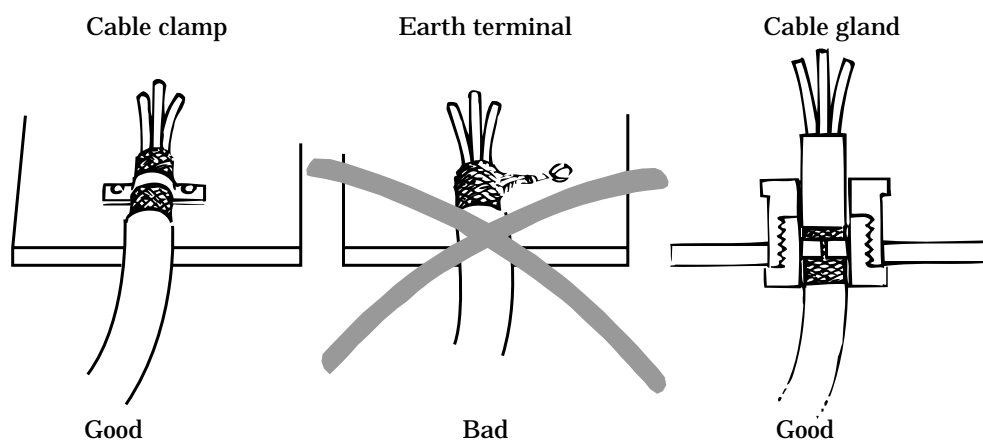limited and the technical documentation should state the radio interference class with which the frequency converter complies. Additionally it is not always clear whether a filter is integrated or whether it has to be purchased and installed separately, and for what motor cable length it is suitable.

Screened/armoured motor and control cables are often necessary and are recommended if a given radio interference protection class is to be complied with.

Power Factor Correction Equipment (PFC)

These units are integrated in networks if the angle of phase difference between voltage and current (cos φ) is to be corrected. This is the case if many inductive current consuming units, such as motors or switching units for lamps, are operated on the mains.

A frequency converter does not create any angle of phase difference; its cos φ is approx. 1. At high frequencies, the capacitors of the PFC system have a lower internal resistance. If high-frequency elements (harmonic waves) remain in the mains voltage, the input current of the PFC unit will rise, the capacitors will heat up and will be subjected to a higher load.

The high-frequency elements from the mains can be blocked out of the installation using chokes either mains or DC link chokes. DC link chokes also prevent resonance from occurring between the inductance of the current consuming units and the capacitance of the correction unit. What must be considered is the fact that the high frequency has a smaller suction effect, which means that in a multiservice control system and audio frequency transformers, a suppression filter is required.

Depending on the regulations of the local electricity supply companies, choke compensation units should be used.

Selection of a frequency converter for variable speed drives

Selecting of a frequency converter for variable speed drives requires a lot of experience. If the experience is not available, it is often useful to visit either a reference plant with similar applications, or exhibitions or trade shows. The following is a brief checklist of points that should be considered:

1. Details of the machine to be controlled
- required plant/machine characteristics
- torque characteristics, stalling torque, acceleration torque
- speed control range, cooling
- power consumption of the converter and the motor
- operating quadrants
- slip compensation (dynamic)
- required ramp-up and ramp-down times
- required braking times, brake operating time
- direct drives, gears, transmission components, moment of mass inertia
- synchronisation with other drives
- operating time, controls
- computer linkage, interfaces, visualisation
- design and protection type
- possibility of integrating decentral intelligence in the frequency converter

2. Environmental details
- installation height, ambient temperature
- cooling requirements, cooling options
- climatic conditions, such as humidity, water, dirt, dust, gas-es
- special regulations, e.g. for mining, the chemical industry, the ship building industry, food technology
- acoustic noise

3. Mains

- mains voltage, voltage fluctuations
- mains performance
- mains frequency fluctuations
- mains interference
- short-circuit and overvoltage protection
- mains drop-out

4. Maintenance, operation, personnel

- training and instruction of operators
- maintenance
- spare parts/spare units

5. Financial criteria

- purchase costs (components)
- space requirement, integrated installation, design
- installation costs
- commissioning of the system
- set-up costs
- operating costs
- efficiency of the system (frequency converter and machine)
- reactive power requirement and compensation for harmonic loads
- Product lifetime

6. Protective measures for operators/converter/motor

- galvanic isolation in accordance with PELV
- phase drop-out
- switching at the converter output
- earth and short-circuit protection
- motor coils to reduce voltage rise times
- electronic thermal monitoring and connection of thermistors

7. Standards/regulations

- national DIN, BS, UL, CSA, VDE, European EN
- international IEC, CE, etc.

8. Environmental considerations

- ability to recycle the product
- manufacturing practice
- energy saving factors

Using this checklist a frequency converter can be selected which covers most of the items as standard, but you should also double check whether:

- the converter has mains or intermediate circuit chokes in order to greatly reduce mains interference
- a RFI filter for class A or B is standard or has to be purchased separately
- motor derating is required if a frequency converter is used
- the converter itself is protected against earth and short-circuit
- the converter reacts adequately in a fault situation.

3. Frequency converters and 3-phase AC motors

The torque (T) developed by asynchronous motors, $T \sim \Phi \times I_L$ normally applies, where I_L is the rotor current and Φ is the air gap flux of the machine.

To optimise torque from the motor, the air gap flux of the machine ($\Phi \sim V/f$) should be kept constant. This means that if the line frequency (f) is changed, the line voltage (V) must be changed proportionally (Fig. 3.01).
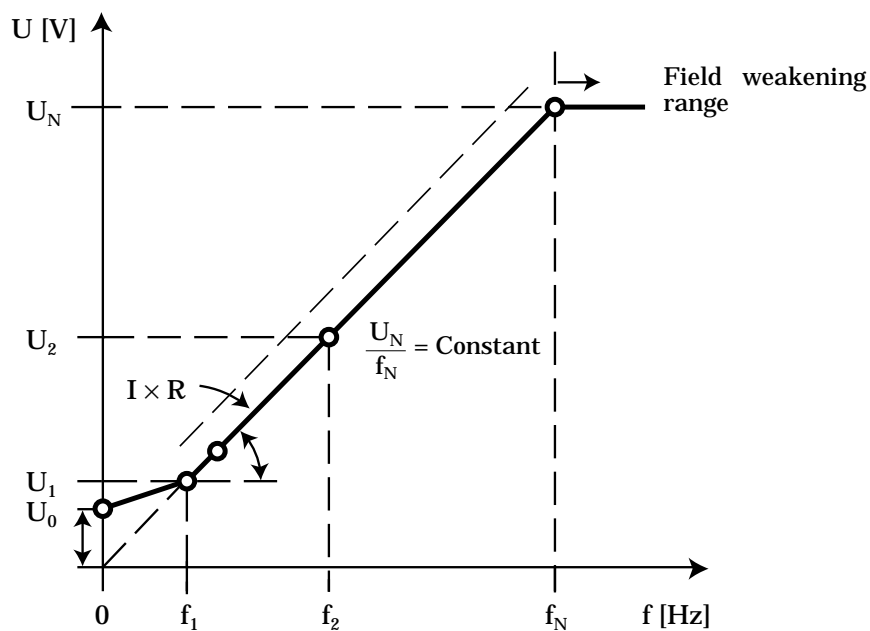
Fig. 3.01   V/f characteristics control

For heavy starts (screw conveyors) and an optimised stalling torque, an extra (start) voltage (V_0) is required. When loaded and in the low speed range (f < 10 Hz) the voltage loss is clearly seen on the active resistance of the stator winding (particularly in small motors), leading to a specific weakening of the air gap flux (Φ).

Example
A 1,1 kW, 3×400 V/50 Hz motor with a stator resistance (one phase) of approx. 8 Ω takes up 3 A at rated load.

The voltage drop at the stator resistance in this case amounts to 8 $\Omega \times$ 3 A = 24 V. The motor manufacturer ensures that this loss is compensated for during rated operation.

40 V at 5 Hz is ideal for controlling the V/f characteristics. If the rated load is impressed on the motor, the motor will take up 3 A and thus have a voltage loss of 24 V. Importantly only 16 V remains for magnetisation and at this voltage, the motor is undermagnetised and generates a reduced torque.

Therefore, in order to maintain the machine flux the voltage drop must be compensated for, and the simplest methods are to:

- increase the output voltage in the lower speed range by open loop control
- regulate the output voltage using the active current components of the converter output current.

This compensation is normally called the I $\times$ R compensation, boost, torque raising, or – at Danfoss – start compensation.

This type of control has limitations where the disturbances are difficult to measure when the load varies strongly (for example on drives with operational fluctuations of the winding resistance of up to 25% between hot and cold state). The voltage increase may have different results. At no load, it can lead to a saturation of the motor flux or – when loaded – to a reduced main flux. In the case of saturation, a high reactive current will flow that leads to heating of the motor. In the case of a load, the motor will develop little torque because of the weak main flux, and may come to a standstill.

Operational conditions of the motor

Compensations

It used to be difficult to tune a frequency converter to a motor because some of the compensational functions, such as "start voltage", "start" and "slip compensation", are difficult to understand.

However, today's more advanced frequency converters automatically control these compensation parameters on the basis of the rated motor frequency, voltage and current. Normally, these compensation settings can also be changed manually.

Load-dependent and load-independent compensation parameters

The compensation parameters ensure optimum magnetisation, and thus maximum torque, both during start-up and all the way from low speed to the full rated motor speed. The output voltage receives a voltage supplement which effectively overcomes the influence of the ohmic resistance of the motor windings at low frequencies. The load-dependent voltage supplement (start and slip compensation) is determined via the current measurement (active current). The load-independent supplement (starting voltage) guarantees an optimum stalling torque in the low speed range.

A motor which is much smaller than the recommended motor size may require an additional, manually adjustable voltage supplement in order to break-away or to guarantee optimum magnetisation in the low speed range.

If several motors are controlled by one frequency converter (parallel operation), load-dependent compensation should not be used.

In the case of frequency converters of the latest generation, this compensation is set automatically by the frequency converter (in standard applications).

Slip compensation

The slip of an asynchronous motor is load-dependent and amounts to some 5% of the rated speed. For a two-pole motor, this means that the slip will be 150 rpm.

However, the slip would be approximately 50% of the required speed if the frequency converter was controlling a motor at 300 rpm (10% of the rated speed).

If the frequency converter is to control the motor at 5% of the rated speed, the motor will not react to a load. This load-dependence is unwanted and the frequency converter is able to fully compensate for this slip by efficiently measuring the active current in the output phases of the frequency converter.

The frequency converter then compensates for the slip by increasing the frequency. This is called active slip compensation.
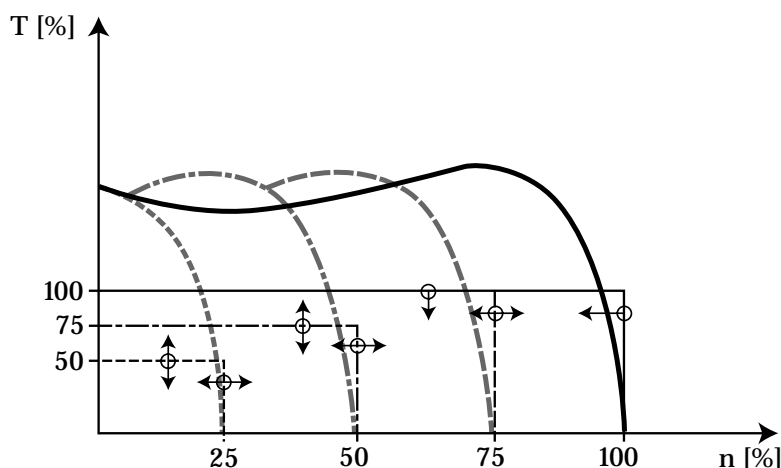
Motor torque characteristics

Current limit

If a frequency converter was capable of supplying a current many times the size of the rated motor current, the torque characteristics of the motor would be as shown in Fig. 1.22 (page 33).

Such high currents can damage both the motor and the power electronic components in the frequency converter and are not required for normal motor operation. Consequently, the frequency converter indirectly limits the motor current by reducing the output voltage and thus the frequency. The current limit is variable and guarantees that the motor current does not constantly exceed the rated value. Since the frequency converter controls the motor speed independent of the load, it is possible to set different limit values within the rated working range of the motor.

The torque characteristics of the motor are within the rated values for some types of frequency converters. However, it is an advantage for the frequency converter to allow a torque of, for example, up to 160% of the rated torque for shorter or longer periods of time. It is also normally possible for a frequency converter controlled motor to be operated in the oversynchronous range up to approximately 200% of the rated speed.

Fig. 3.02   The torque characteristics of the frequency converter controlled motor can be set in "rectangles"

The frequency converter is not able to deliver a higher voltage than the voltage of the mains supply which leads to a declining voltage-to-frequency ratio if the rated speed is exceeded. The magnetic field weakens and the torque generated by the motor drops by 1/n.
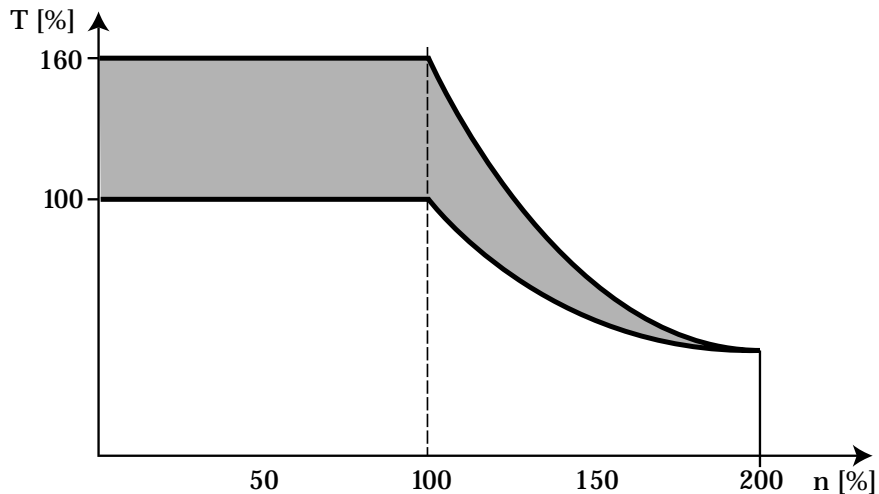
Fig. 3.03   Motor torque and over-torque

The maximum output current of the frequency converter remains unchanged. This leads to a constant power performance of up to 200% of the rated speed.
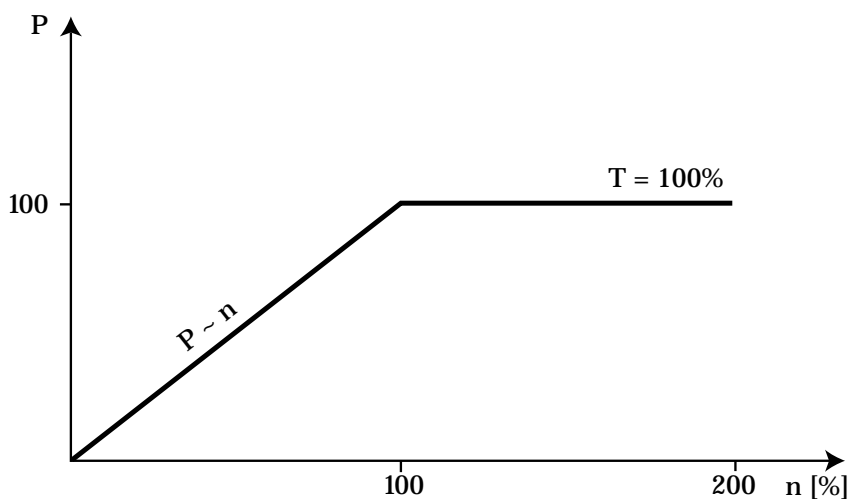
Fig. 3.04   Motor performance

The motor speed can be stated in three different ways: revolutions per minute [rpm], Hertz [Hz] or as a percentage of the rated motor speed [%]. The point of reference is always the motor speed at rated frequency.

Fig. 3.05   Indication of speed (here for a 2-pole motor)

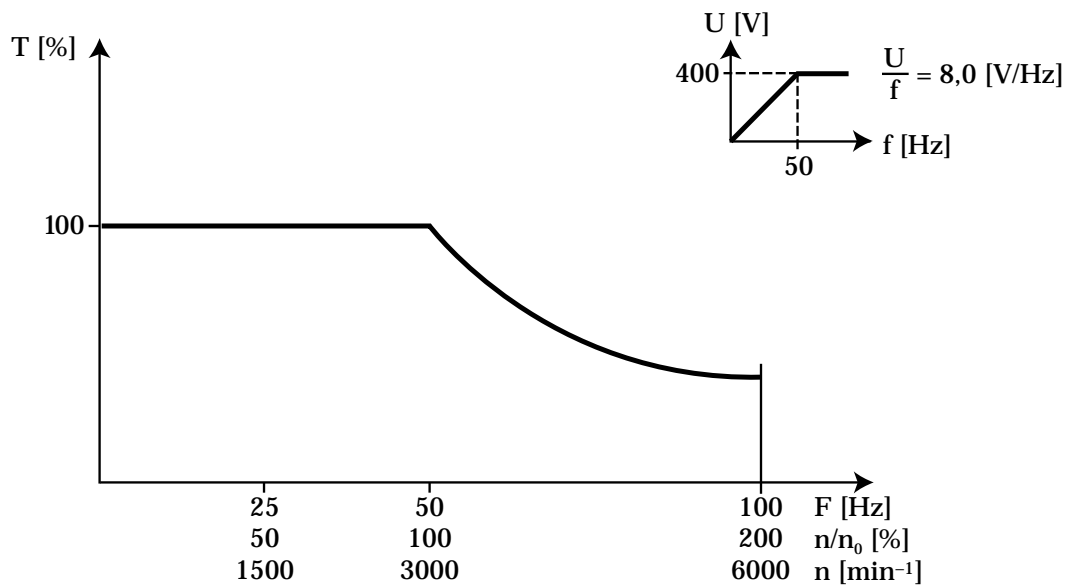A change of the voltage-to-frequency ratio influences the torque characteristics. The illustration below shows the torque characteristics in connection with a reduction of the voltage-to-frequency ratio to 6.7 [V/Hz].
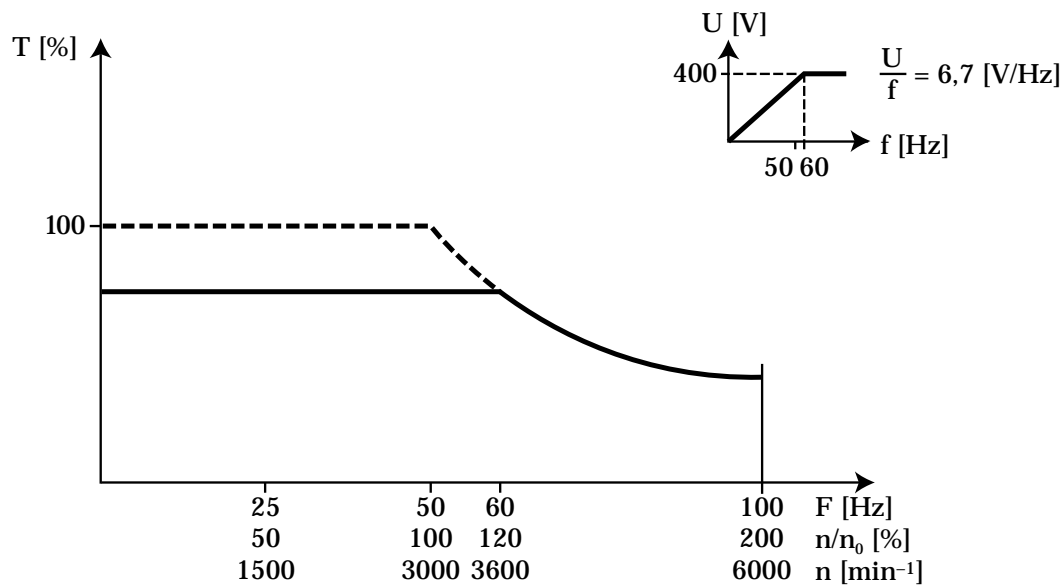

Fig. 3.06   Torque in a different setting of the V/f ratio

Requirements from advanced digital frequency converters

Recent developments in power electronics, micro-processor technology and integrated circuits have had a strong influence on drive technology, particularly in terms of developing digital drives with a higher processing speed and increased accuracy.

Other advantages of digital drive control include :
• improved repeatability and stability of the control parameters
• easier control of control measures
• flexibility of application-specific functions
• more precise control over a larger range.

The old analogue drives were adjusted using a potentiometer or passive components which can lead to an offset and temperature drift problems. On the other hand, with digital control all the control parameters can be stored in an EEPROM.

The micro-processor allows easy realisation of functions such as disabling of control, data set switching, etc. Even complete operating programs (process control) and drive-specific intelligence can be stored in the frequency converter. This has made today's AC drives suitable for the type of wide speed range, high dynamic response applications previously only handled by DC inverters.

It has also led to the abandonment of V/f characteristics control by the frequency converter and the introduction field-oriented or vector control.

Sizing a
frequency converter

When determining the rating of a frequency converter at a given load the first step is to consider the load characteristics. There are four different methods for calculating the required output performance and the choice of method depends on the motor data.

Load characteristics

Before the frequency converter size can be determined, a distinction must be made between the two most widely used load characteristics (see Fig. 1.32 – page 44).
The reasons for distinguishing between load characteristics are the following:
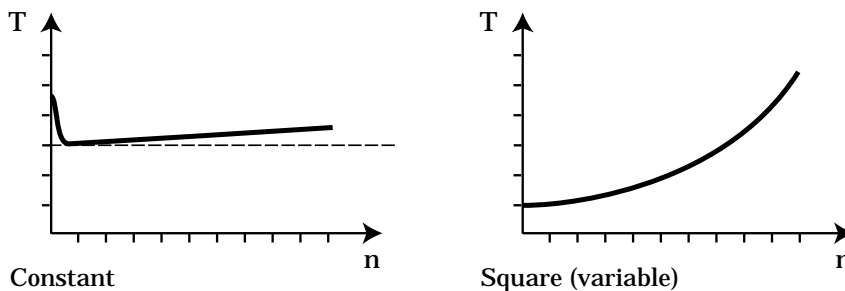
Fig. 3.07   Constant and square load torque

- When the speed of centrifugal pumps and fans increases, the power requirement increases by the speed cubed ($P = n^3$).
- The normal working range of centrifugal pumps and fans is the speed range of 50 to 90%. The load ratio increases by the speed squared, i.e. approx. 30 to 80%.

These two factors are shown in the torque characteristics of a frequency converter controlled motor.

Fig. 3.08 and Fig. 3.09 show torque characteristics for two different frequency converter sizes – one of them (Fig. 3.09) is one power range lower than the other. For both torque characteristics the same load characteristics were entered for a centrifugal pump.

In Fig. 3.08, the total working range of the pump (0-100%) lies within the rated values of the motor. Since the normal working range of the pump is 30-80%, a frequency converter with a lower output can be chosen.
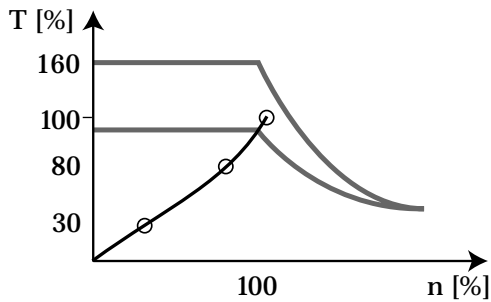

Fig. 3.08
"Big" frequency converter
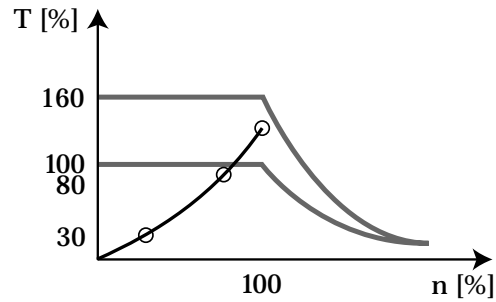
Fig. 3.09
"Smaller" frequency converter

If the load torque is constant, the motor must be able to generate more than the load torque as the excess torque is used for acceleration.

An overload torque of 60% generated by the frequency converter for a short time is enough for acceleration and high starting torque, for example in connection with conveyor belts. The overload torque also guarantees that the system is able to cope with sudden increases of load. A frequency converter that does not allow any overload torque has to be selected such that the acceleration torque (T_B) lies within the rated torque.

Fig. 3.10   Overload torque is used for acceleration

When the load characteristics have been determined, there are four different sets of motor data for deciding the power size of the frequency converter.

1. The frequency converter can be determined quickly and precisely on the basis of the current I_M which the motor takes up. If the motor is not fully loaded, the motor current could be measured on a similar system in full operation.
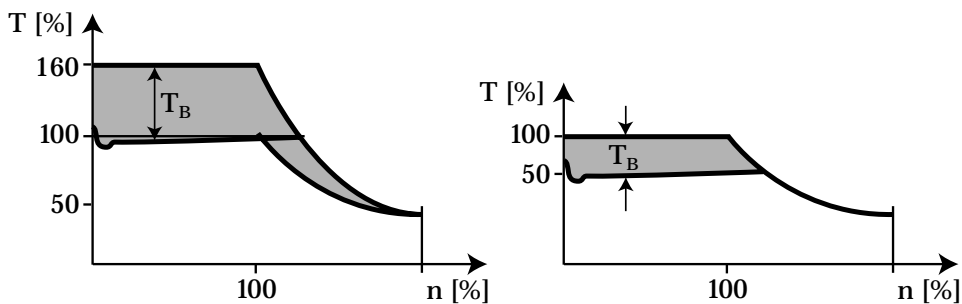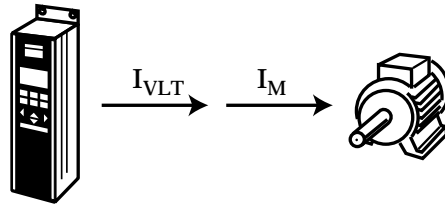

Fig. 3.11   Selection of a frequency converter on the basis of rated current

Example: A 7.5 kW, 3 x 400 V motor draws 14.73 A.

Referring to the technical data of the frequency converter, a frequency converter is selected that has a maximum continuous output current higher than or equal to 14.73 A at constant or square torque characteristics.

Note
If a frequency converter is selected on the basis of power (methods 2-4), it is important for the calculated power and the power stated under the technical data for the frequency converter to be compared at the same voltage. This is not necessary if the frequency converter is calculated on the basis of a current (method 1) since the output current of the frequency converter influences the other data.

2. The frequency converter can be selected on the basis of the apparent power S_M taken up by the motor and the apparent power delivered by the frequency converter.
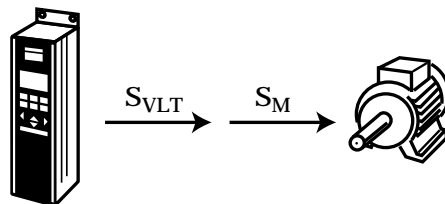
Fig. 3.12   Selection of a frequency converter based on apparent power

Example: A 7.5 kW, 3 × 400 V motor draws 14.73 A

$$S_M = \frac{U \times I \times \sqrt{3}}{1000} = \frac{400 \times 14.73 \times \sqrt{3}}{1000} = 10.2 \text{ kVA}$$
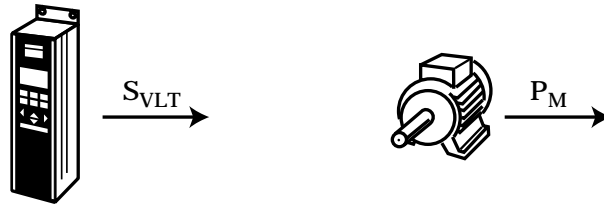
Referring to the technical data of the frequency converter, a frequency converter is selected whose maximum continuous output is higher than or equal to 10.2 kVA at constant or square torque characteristics.

3. A frequency converter can also be selected in accordance with the power PM generated by the motor. However, since cos φ and efficiency η change with the load, this method is imprecise.

Fig. 3.13   Selection of a frequency converter according to shaft output power

Example:
A 3 kW motor with an efficiency and cos φ of 0.80 or 0.81, respectively, draws as follows

$$S_M = \frac{P_M}{\eta \times \cos \varphi} = \frac{3{,}0}{0.80 \times 0.81} = 4.6 \text{ kVA}$$

A frequency converter is selected – referring to the technical data of the frequency converter – that has a maximum continuous output higher than or equal to 4.6 kVA at constant or square torque characteristics.

4. For practical reasons, the power rating of most frequency converters follows the standard series of the asynchronous motors. Consequently, frequency converters are often selected on this basis but this can lead to imprecise sizing, in particular if the motor is not subjected to a full load.
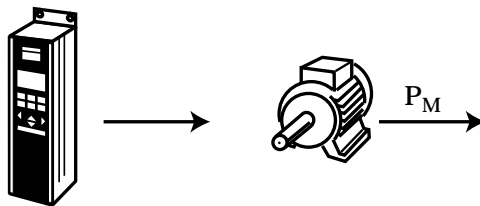
Fig. 3.14   Selection of a frequency converter on the basis of the standard series of motors

Current distribution in the frequency converter (cos φ of the motor)

The current for magnetising the motor is supplied by the capacitor in the frequency converter intermediate circuit. The magnetising current is a reactive current that flows between the capacitor and motor (Fig. 3.15).
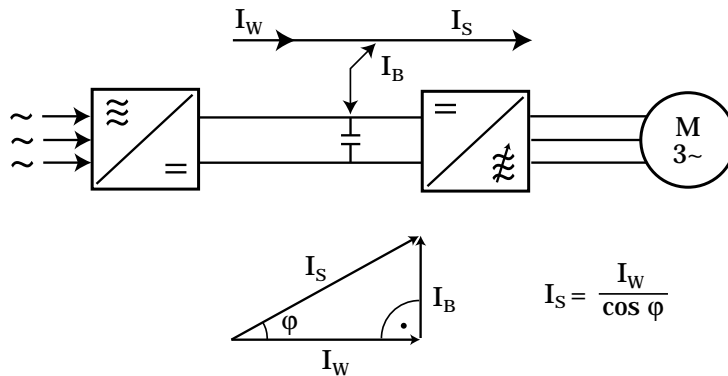
Fig. 3.15   Currents in the frequency converter

Only the active current (I_W) is drawn from the mains. That is why the output current of the frequency converter is always greater than the input current. In addition to the active current, the losses (I_{loss}) are taken up by mains, which can be seen clearly in the no-load operation.

Example:
The no-load current of a four-pole 1.1 kW motor is 1.6 A. The output current of the connected frequency converter is approximately. 1.6 A and the input current at no-load operation is almost zero.

Motor manufacturers normally state the cos φ of the motor at rated current. At a lower value of cos φ (e.g. reluctance motors), the rated motor current – at the same power and rated voltage – will be bigger, as shown in the following equation:

$$I_S = \frac{I_W}{\cos \varphi}$$

If the frequency converter is sized in accordance with the rated motor current (method 1), there will be no reduction of the rated motor torque.
A capacitor placed at the motor terminals for the purpose of reactive current compensation must be removed. The high

switching frequency of the frequency converter makes the capacitor work as a short-circuit and causes a high rise in the motor current. The converter will see this as an earth or short-circuit fault and switch off.

Control of motor speed

The output frequency of the frequency converter, and thus the motor speed, is controlled by one or more signals (0-10 V; 4-20 mA, or voltage pulses) as a speed reference. If the speed reference increases, the motor speed goes up and the vertical part of the motor torque characteristics is shifted to the right (Fig. 3.16).
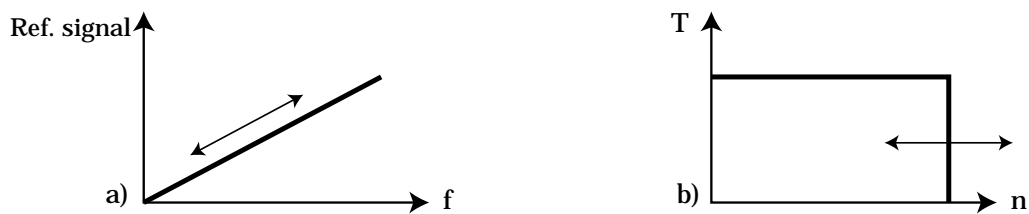
Fig. 3.16   Function between reference signal and torque characteristics of the motor

If the load torque is smaller than the available motor torque, the speed will reach the required value. As shown by fig 3.17, the load torque characteristics intersect the motor torque characteristics in the vertical part (at point A). If the intersection is in the horizontal part (point B), the motor speed cannot continuously exceed the corresponding value. The frequency converter enables short current limit overshoots without tripping (point C), but it is necessary to limit the overshoot in time.
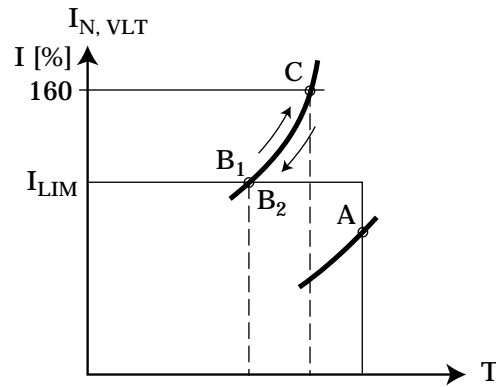
Fig. 3.17   The motor current may exceed the current limit for a short time

Acceleration and deceleration ramps

The acceleration ramp indicates the rate at which speed is increased and is stated in the form of an acceleration time t_{acc}. These ramps are mostly based on the rated motor frequency, e.g. an acceleration ramp of 5 sec. means that the frequency converter will take 5 seconds to go from 0 to the rated motor frequency (f_n = 50 Hz).
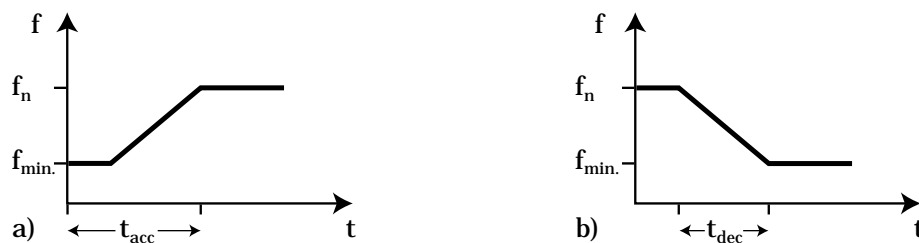
Fig. 3.18   Acceleration and deceleration times

The deceleration ramp indicates how fast the speed is decreased. It is stated in the form of a deceleration time t_{dec}.

It is possible to go directly from acceleration to deceleration, since the motor always follows the output frequency of the inverter.

If the moment of inertia of the motor shaft is known, the optimum acceleration and deceleration times can be calculated.

$$t_{acc} = J \times \frac{n_2 - n_1}{(T_{acc} - T_{fric}) \times 9.55}$$

$$t_{dec} = J \times \frac{n_2 - n_1}{(T_{dec} + T_{fric}) \times 9.55}$$

J is the moment of inertia of the motor shaft.
T_{fric} is the friction torque of the system.
T_{acc} is the overshoot torque used for acceleration.
T_{dec} is the braking torque that occurs when the speed reference is reduced.
n_1 and n_2 are the speeds at frequencies f_1 and f_2 .

If the frequency converter allows an overload torque for a short time, the acceleration and deceleration torques are set to the rated motor torque, T. In practice, the acceleration and deceleration times are normally identical.

Example
$J = 0,042$ kgm^2 $n_1 = 500$ min^{-1} $n_2 = 1000$ min^{-1}
$T_{fric} = 0.05 \times M_N$ $T_N = 27$ Nm

$$t_{acc} = J \times \frac{n_2 - n_1}{(T_{acc} - T_{fric}) \times 9.55} = 0.042 \times \frac{1000 - 500}{(27,0 - (0,05 \times 27,0)) \times 9.55} = 0.1 \text{ [s]}$$

Dynamic brake operation
When the speed reference is reduced, the motor acts as a generator and brakes. The braking deceleration depends on the size of the motor load.

Motors connected directly to mains deliver the braking power straight back to mains.

If a motor is controlled by a frequency converter, the braking power is stored in the frequency converters intermediate circuit. If the braking power exceeds the power loss of the frequency converter, the voltage in the intermediate circuit increases.

The intermediate circuit voltage can rise until the frequency converter trips for protection and it is sometimes necessary to place a load on the intermediate circuit in the form of a brake module and an external resistor to absorb the braking power.

(Using a brake module and resistor enables heavy loads to be braked quickly. However, they can cause heating problems. An alternative is a regenerative braking unit. These units are used for frequency converters with an uncontrolled rectifier and feed the braking energy back to the mains.

In frequency converters with controlled rectifiers, the braking power can be fed back to the mains (see Fig. 3.19) by, for example, an inverter in anti-parallel connection across the rectifier.
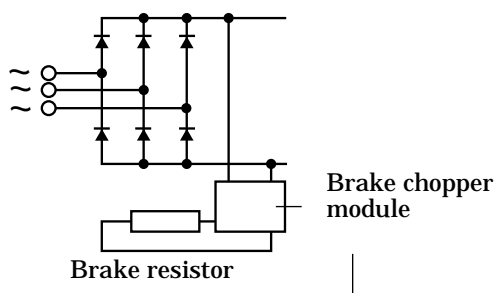
Fig. 3.19
Brake module and resistor connection
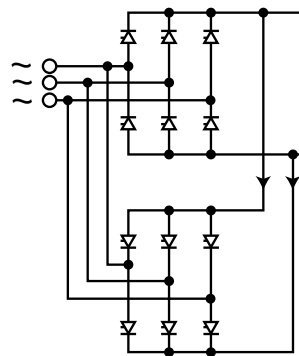
Fig. 3.20
Inverter in anti-parallel

The DC brake is another way of braking the motor. A DC voltage across two motor phases is used to generate a stationary magnetic field in the stator. As the braking power remains in the motor and overheating may occur it is recommended to set the DC brake in the lower speed range so that the rated motor current is not exceeded. In general, DC braking is limited by time.

Reversing

The direction of rotation in asynchronous motors is determined by the phase sequence of the supply voltage.

If two phases are swapped, the direction in which the motor rotates changes and the motor reverses.

Most motors have been designed to make the motor shaft turn clockwise if connection is made as follows:
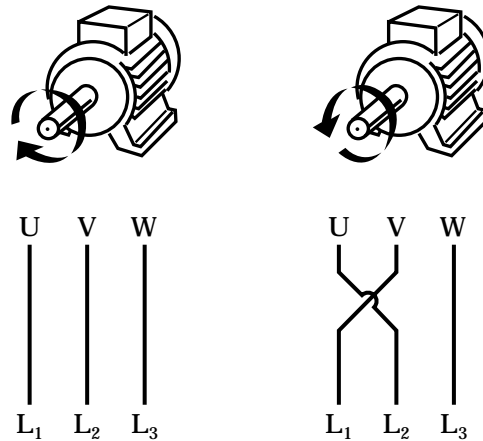
Fig. 3.21   The direction of rotation of the motor changes with changes in the phase sequence

The phase sequence on the output terminals of most frequency converters also follows this principle.

A frequency converter can reverse the motor by electronically changing the phase sequence. Reversing is accomplished by either using a negative speed reference or a digital input signal. If the motor requires a specific direction of rotation when first commissioned, it is important to know the frequency converters factory default setting.

Since a frequency converter limits the motor current to the rated value, a motor controlled by a frequency converter can be reversed more frequently than a motor connected directly to mains.
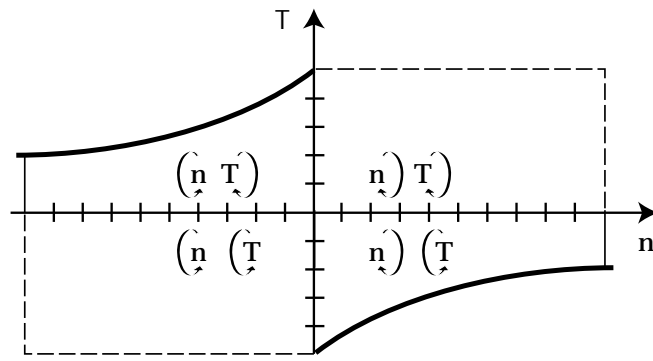
Fig. 3.22   Braking torque of the frequency converter during reversing

Ramps

All frequency converters have ramp functions to provide smooth operating conditions. These ramps are adjustable and guarantee that the speed reference is only able to increase or decrease at a preset rate.

Fig. 3.23   Variable ramp times

Ramp times can be set to such low values that in some situations the motor cannot follow the preset speed.

This leads to an increase of the motor current until the current limit is reached. In the case of short ramp-down times (t_{-a}), the voltage in the intermediate circuit may increase to such a level that the protective circuit of the frequency converter will stop the converter.

The optimum ramp times can be calculated on the basis of the formulas given below:

$$t_a = J \times \frac{n}{(T_N - T_{fric}) \times 9.55}$$

$$t_{-a} = J \times \frac{n}{(T_N + T_{fric}) \times 9.55}$$

t_a: ramp up
t_{-a}:   ramp down
n:
T_N: rated motor torque
T_{fric}:   friction torque
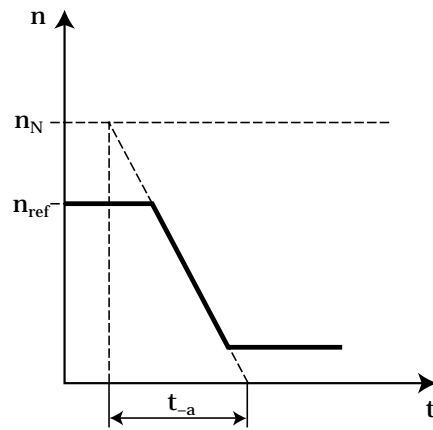
Fig. 3.24   Setting of ramp times

Ramp times are usually selected on the basis of the rated motor speed.

Monitoring

Frequency converters can monitor the process being controlled and intervene in case of operational disturbance.

This monitoring can be divided into three areas: process plant, motor and frequency converter.

Monitoring the plant is based on output frequency, output current and motor torque. Based on these values, a number of limits can be set which intervene in the control function if they are exceeded. These limits could be the smallest permissible motor speed (min. frequency), the highest permissible motor current (current limit) or the highest permissible motor torque (torque limit).

If the limits are exceeded, the frequency converter can, for example, be programmed to give a warning signal, to decrease the motor speed or to stop the motor as fast as possible.

Example:
In an installation using a V-belt as a connection between the motor and the rest of the installation, the frequency converter can be programmed to monitor the V-belt.

As we would expect the output frequency to increase more quickly than the preset ramp if the V-belt breaks, the frequency can be used to either give a warning or stop the motor if these situations occur.

Motor monitoring via the frequency converter is possible based on a calculation of the thermal conditions in the motor or by connecting a thermistor to the motor. Like a thermal switch, the frequency converter can prevent motor overload. The output frequency is among the calculations made by the frequency converter. This guarantees that the motor is not overloaded at low speeds if the internal ventilation is reduced. Today's frequency converters are also able to protect motors with forced ventilation if the current is too high.

Unit monitoring is traditionally carried out in the way that the frequency converter trips in the case of an overcurrent. Some frequency converters allow a short overcurrent. The microprocessor in the frequency converter is able to sum the motor current and the time to ensure that the frequency converter is optimally used without overloading.

Motor load and motor heating

When a motor is connected to a frequency converter it must be kept at the correct temperature, and this is subject to two types of influence:

- If the speed decreases, the cooling air volume goes down.
- If a non-sinusoidal motor current is present, more heat is generated in the motor.

At low speeds the motor fan is not able to supply enough air for cooling. This problem arises if the load torque is constant throughout the control range. This lower ventilation determines the level of torque allowed during continuous loads. If the motor runs continuously – at 100% rated torque – at a speed which is less than half the rated speed, the motor requires extra air for cooling (the grey areas in Fig. 3.25).

Alternatively the load ratio of the motor can be reduced by selecting a bigger motor. However, care must be taken not to oversize the motor too much for a given frequency converter.
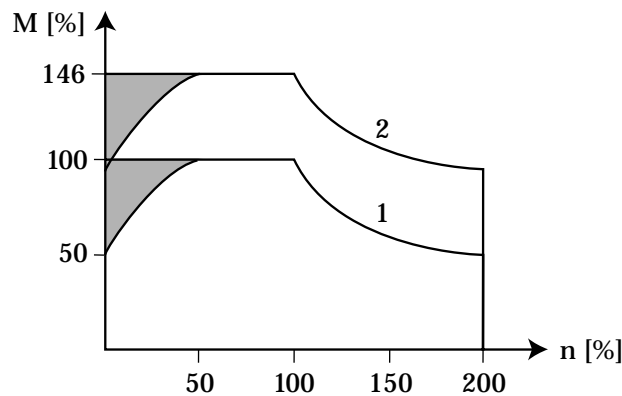
Graph 1: Motor of rated size, e.g. 15 kW
Graph 2: Oversize motor, e.g. 22 kW

Fig. 3.25   The need for external ventilation for a motor at rated size and an oversize motor

If the motor current is not sinusoidal, it should not be subjected to 100% load all the time as it will receive harmonic currents that increase its temperature. The size of the harmonic currents determines the amount of heat.
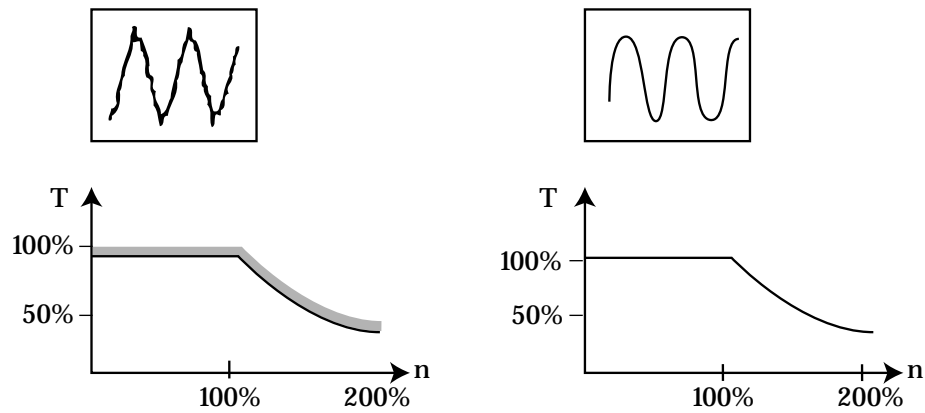
Fig. 3.26   A non-sinusoidal current generates extra heat in the motor

Efficiencies

The efficiency η of a unit is defined as the ratio between output power P_2 and power P_1.

$$\eta = \frac{P_2}{P_1}$$

The difference between P_1 and P_2 is defined as power loss P_v, i.e. power that is dissipated as heat in the unit.
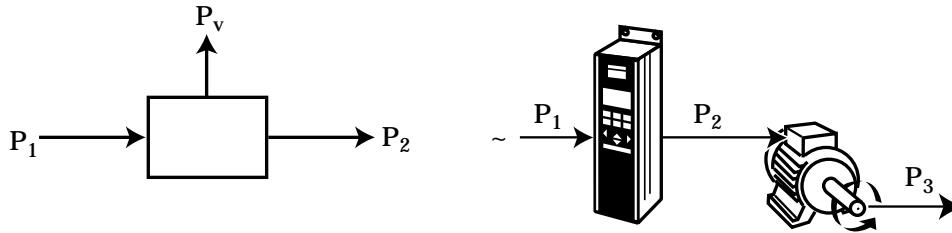
Fig. 3.27   Output, power intake and efficiencies

The efficiency can be calculated for the frequency converter alone, for the motor alone or for the frequency converter and motor (system efficiency).

Efficiency of the frequency converter $\quad \dfrac{P_2}{P_1}$

Efficiency of the motor $\quad \dfrac{P_3}{P_2}$

System efficiency $\quad \dfrac{P_3}{P_1}$
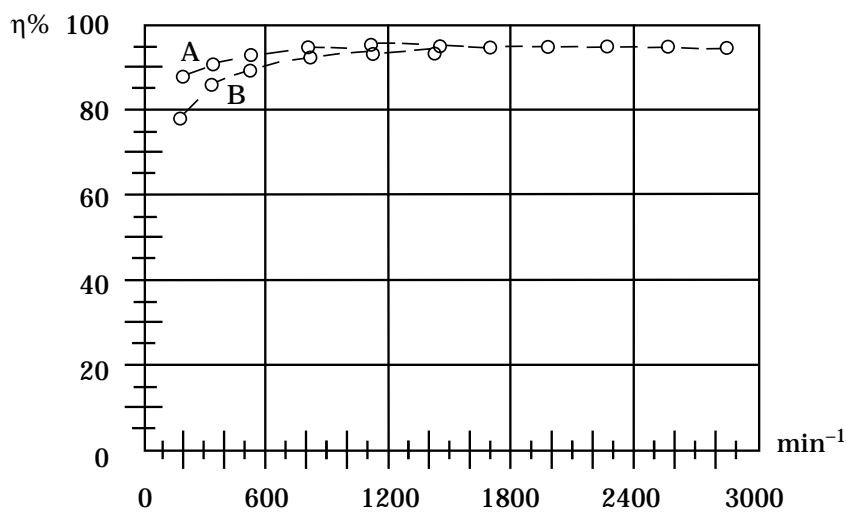
Fig. 3.28   Efficiency of frequency converter at 100% (A)
and 25% (B) load
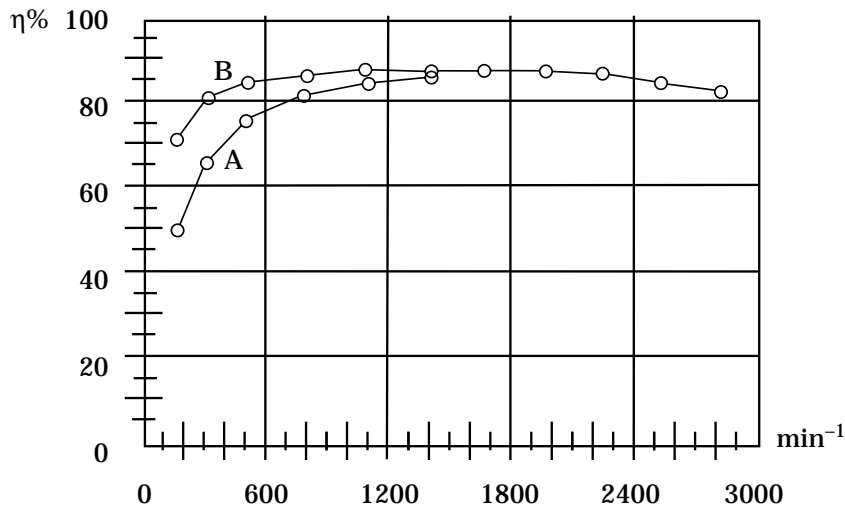
*Fig. 3.29   Efficiency of a typical motor (2-pole) at 100% (A) and
25% (B) load*

The graphs show that the efficiency of the motor has a major influence on the system efficiency. The efficiency of the frequency converter is high throughout the control range, both at high and at low levels of load.

It can also be seen that efficiencies are lowest at low speeds. However, this does not mean that the total losses are the highest at low speeds.
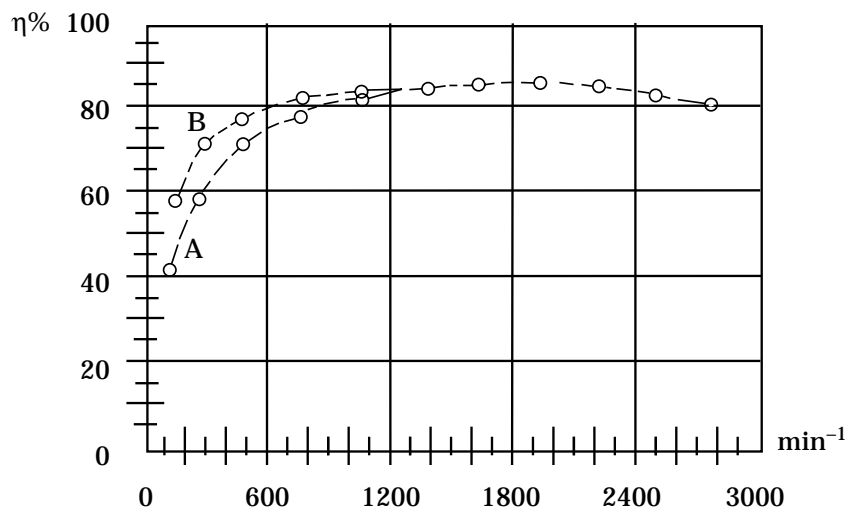
*Fig. 3.30   Efficiency of a frequency converter and motor (2-pole)
at 100% (A) and 25% (B) load*

Examples from Fig. 3.30:

1. $n = 800 \text{ min}^{-1}$

$P_3 = 9628 \text{ W}$

$\eta = 77.3\%$

$P_1 = \dfrac{P_3}{\eta} = 12455.4 \text{ W}$

$P_v = P_1 - P_3 = 2827.4 \text{ W}$

2. $n = 500 \text{ min}^{-1}$

$P_3 = 1500 \text{ W}$

$\eta = 70\%$

$P_1 = \dfrac{P_3}{\eta} = 2143 \text{ W}$

$P_v = P_1 - P_3 = 643 \text{ W}$

The high efficiencies of frequency converters offer several advantages:

- The higher the efficiency, the smaller the thermal loss that has to be removed from the installation. This is important if the frequency converter is integrated in a control panel.

- The less thermal loss is present in the semi-conductors and the coils of the frequency converter, the longer the life-time.

- The higher the efficiency the lower the energy consumption.

2. Frequency converters

Since the late 1960's, frequency converters have undergone extremely rapid changes, largely as a result of the development of microprocessor and semi-conductor technologies and their reduction in prices. However, the basic principles of frequency converters remains the same.

Frequency converters can be divided into four main components:
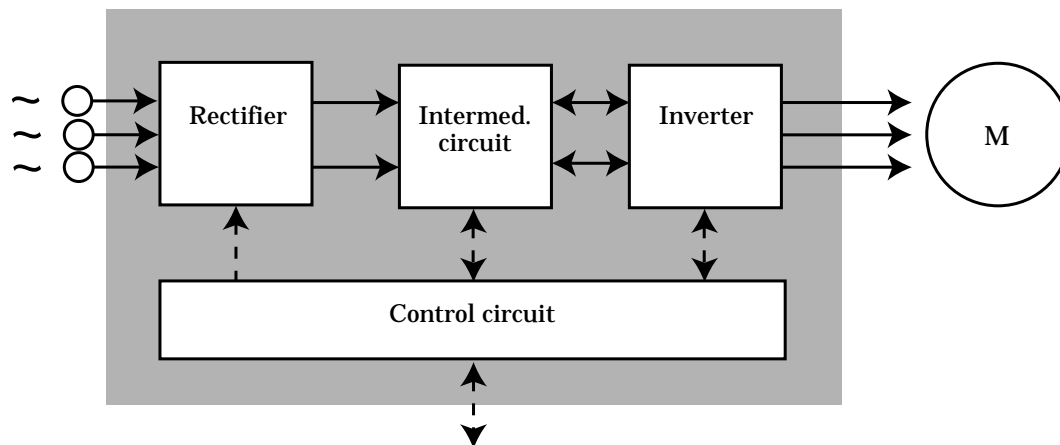
Fig. 2.01   Simplified frequency converter

1. The rectifier, which is connected to a single/three-phase AC mains supply and generates a pulsating DC voltage. There are two basic types of rectifiers – controlled and uncontrolled.

2. The intermediate circuit. There are three types:
   a) one, which converts the rectifier voltage into a direct current.
   b) one, which stabilises or smoothes the pulsating DC voltage and places it at the disposal of the inverter.
   c) one, which converts the constant DC voltage of the rectifier to a variable AC voltage.

3. The inverter which generates the frequency of the motor voltage. Alternatively, some inverters may also convert the constant DC voltage into a variable AC voltage.

4. The control circuit electronics, which transmit signals to – and receive signals from – the rectifier, the intermediate circuit and the inverter. The parts that are controlled in detail depends on the design of the individual frequency converter (see Fig. 2.02).

What all frequency converters have in common is that the control circuit uses signals to switch the inverter semi-conductors on or off. Frequency converters are divided according to the switching pattern that controls the supply voltage to the motor.

In figure 2.02, which shows the different design/control principles:

1 is a controlled rectifier,
2 is an uncontrolled rectifier,
3 is a variable DC intermediate circuit,
4 is a constant DC voltage intermediate circuit,
5 is a variable DC intermediate circuit,
6 is a PAM inverter and
7 PWM inverter.
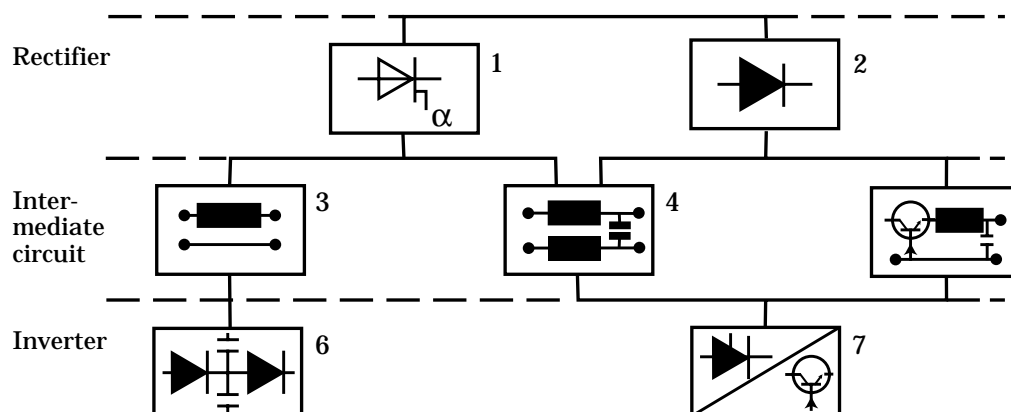
Current Source Inverter: CSI
(1 + 3 + 6)

Pulse-amplitude-modulated converter: PAM
(1 + 4 + 7) (2 + 5 + 7)

Pulse-width-modulated converter: PWM/VVC[plus]
(2 + 4 + 7)

Fig. 2.02   Different design/control principles

Direct converters, which do not have an intermediate circuit should also be briefly mentioned for completeness. These converters are used in the Mega-watt power range to generate a low-frequency supply directly from the 50 Hz mains and their maximum output frequency is about 30 Hz.

The rectifier

The supply voltage is a three-phase AC voltage or a single-phase AC voltage with a fixed frequency (e.g 3 × 400 V/50 Hz or 1 × 240 V/50 Hz) and their characteristic values can be illustrated as:
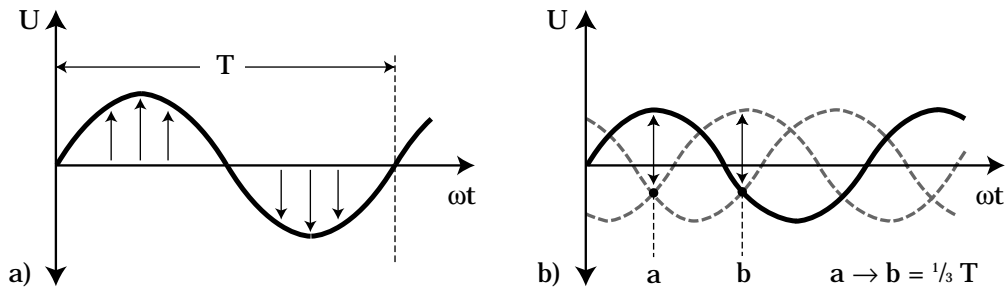
Fig. 2.03   Single- and three-phase AC voltage

In the illustration the three phases are displaced in time, the phase voltage constantly changes direction, and the frequency indicates the number of periods per second. A frequency of 50 Hz means that there are 50 periods per second (50 × T), i.e. one period lasts for 20 milliseconds.

The rectifier of a frequency converter consists either of diodes, thyristors or a combination of both. A rectifier consisting of diodes is uncontrolled and a rectifier consisting of thyristors is controlled. If both diodes and thyristors are used, the rectifier is semi-controlled.

Uncontrolled rectifiers
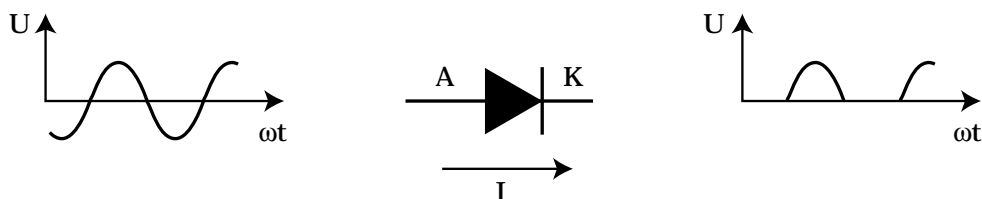
Fig. 2.04   Diode mode of operation

Diodes allow current to flow in one direction only: from the anode (A) to the cathode (K). It is not possible – as is the case with some other semi-conductors – to control the current strength. An AC voltage over a diode is converted to a pulsating DC voltage. If a three-phase AC voltage is supplied to an uncontrolled three-phase rectifier, the DC voltage will continue to pulsate.
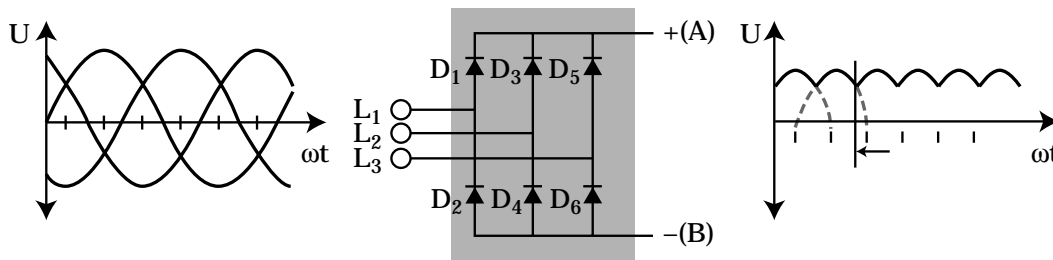
Fig. 2.05   The uncontrolled rectifier

Fig 2.05 shows an uncontrolled three-phase rectifier, consisting of two groups of diodes. One group consists of diodes D_1, D_3 and D_5. The other group consists of diodes D_2, D_4 and D_6. Each diode conducts $^1/_3$ of the periodic time (120°). In both groups, the diodes conduct in sequence. Periods in which both groups control are displaced by $^1/_6$ of the periodic time T (60°) in relation to each other.

Diodes $D_{1,3,5}$ conduct when the positive voltage is applied. If the voltage of phase L_1 reaches the positive peak value, terminal A assumes the value of phase L_1. Above the two other diodes are reverse voltages sized U_{L1-2} and U_{L1-2}.

This also applies to diode group $D_{2,4,6}$. Here terminal B receives the negative phase voltage. If at a given time L_3 reaches the negative threshold value, diode D_6 conducts. The two other diodes are subject to reverse voltages of sizes U_{L3-1} and U_{L3-2}.

The output voltage of the uncontrolled rectifier is the difference value of the voltages of the two diode groups. The mean value of the pulsating DC voltage is 1.35 × mains voltage.
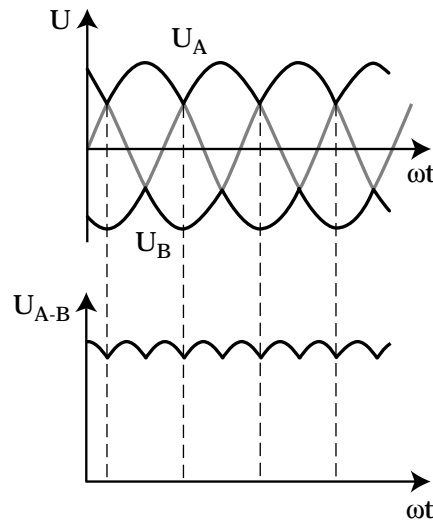
Fig. 2.06   The output voltage of the uncontrolled three-phase rectifier

Controlled rectifiers

In controlled rectifiers, the diodes are replaced by thyristors. Like the diode, the thyristor only allows the current to flow from the anode (A) to the cathode (K). However, the difference between the two devices is that the thyristor has a third terminal "Gate" (G). This gate must be controlled by a signal before the thyristor conducts. When a current flows through the thyristor, the thyristor will conduct the current until it becomes zero.

The current cannot be interrupted by a signal on the Gate. Thyristors are used in rectifiers as well as in inverters.

The signal to the Gate is the control signal α of the thyristor, which is a time delay, stated in degrees. The degree value indicates the delay between the voltage zero crossing and the time when the thyristor is conducting.
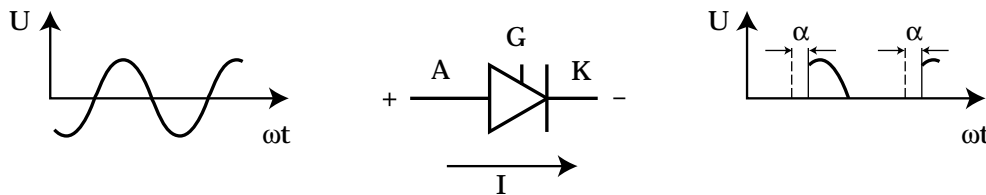
Fig. 2.07   Thyristor mode of operation

If symbol α is between 0° and 90°, the thyristor coupling is used as a rectifier, when it is between 90° and 300° the thyristor is used as an inverter.
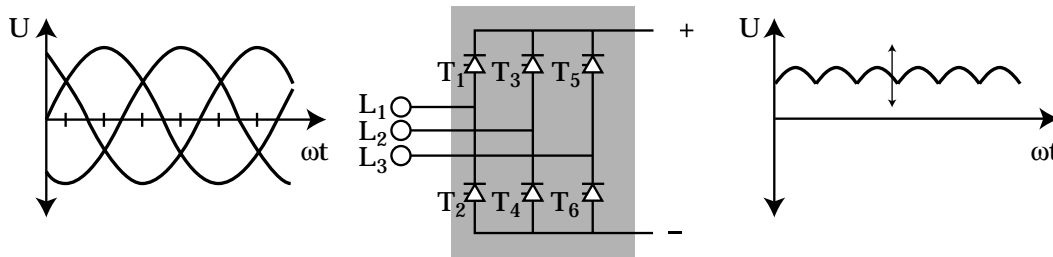
Fig. 2.08   The controlled three-phase rectifier

The controlled rectifier is basically the same as an uncontrolled rectifier except that the thyristor is controlled by α and starts conducting from the point where a normal diode begins to conduct, up to a point 30° behind the voltage zero crossing.

Regulating α allows variation of the value of the rectified volt-
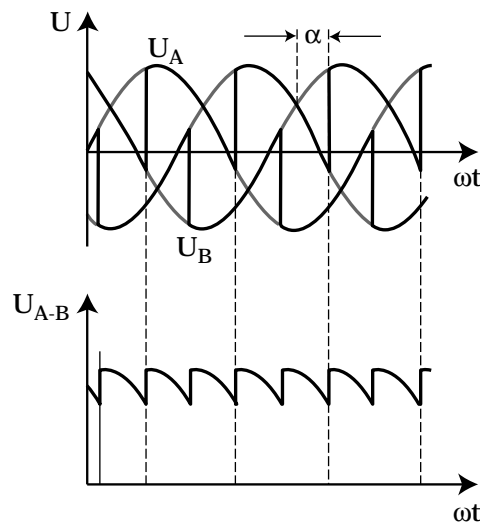
Fig. 2.09   The output voltage of the controlled three-phase rectifier

age. The controlled rectifier supplies a DC voltage with a mean value of $1.35 \times$ mains voltage $\times \cos \alpha$.

Compared to the uncontrolled rectifier, the controlled rectifier causes major losses and disturbances in the supply mains, because the rectifier draws a higher reactive current if the thyristors conduct for a short time.

However the advantage of controlled rectifiers is that energy can be fed back into the mains supply.

The intermediate circuit

The intermediate circuit can be seen as a storage facility from which the motor is able to draw its energy via the inverter. It can be built according to three different principles depending on the rectifier and inverter.

Current-source inverters (I-converters)
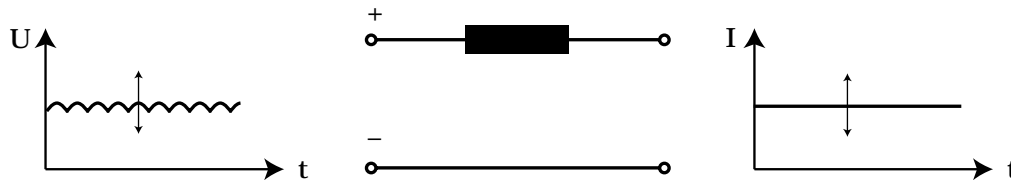
Fig. 2.10   Variable DC intermediate circuit

On current-source inverters the intermediate circuit consists of a large coil and is only combined with the controlled rectifier. The coil transforms the variable voltage from the rectifier into a variable direct current. The load determines the size of the motor voltage.

Voltage-source inverters (U-converters)
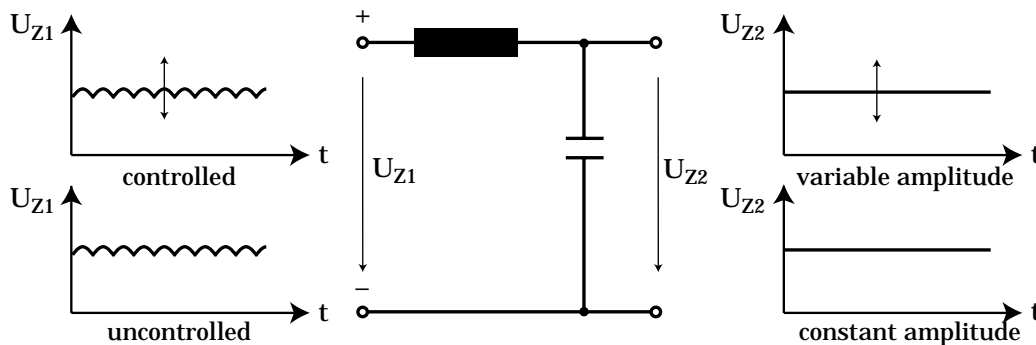
Fig. 2.11   Constant DC voltage intermediate circuit

On voltage-source inverters the intermediate circuit consists of a filter containing capacitor and can be combined with both types of rectifier. The filter smoothes the pulsating DC voltage (U_{Z1}) of the rectifier.

In a controlled rectifier, the voltage is constant at a given frequency, and supplied to the inverter as pure DC voltage (U_{Z2}) with variable amplitude.

In uncontrolled rectifiers, the voltage at the input of the inverter is a DC voltage with constant amplitude.

Variable DC voltage intermediate circuit
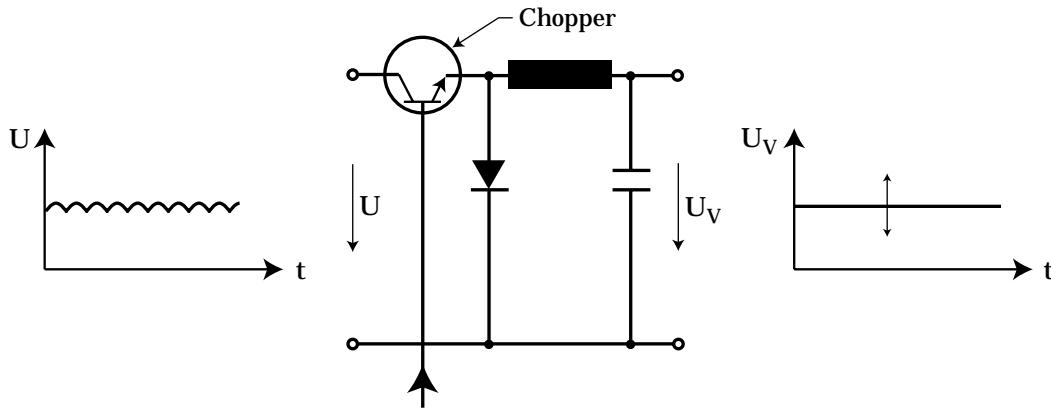
Fig. 2.12   Variable voltage intermediate circuit

Finally, in variable DC voltage intermediate circuits a chopper can be inserted in front of a filter, as shown in figure 2.12.

The chopper has a transistor, which works as a switch to turn the rectified voltage on and off. The control circuit regulates the chopper by comparing the variable voltage after the filter (U_v) with the input signal. If there is a difference, the ratio is regulated by the time during which the transistor is conducting and the time when it blocks. This varies the effective value and size of the DC voltage and can be expressed as:

$$U_V = U \times \frac{t_{on}}{t_{on} + t_{off}}$$

When the chopper transistor interrupts the current, the filter coil makes the voltage across the transistor infinitely high. In order to avoid this, the chopper is protected by a free-wheeling diode. When the transistor opens and closes as shown in fig. 2.13, the voltage is highest in situation 2.
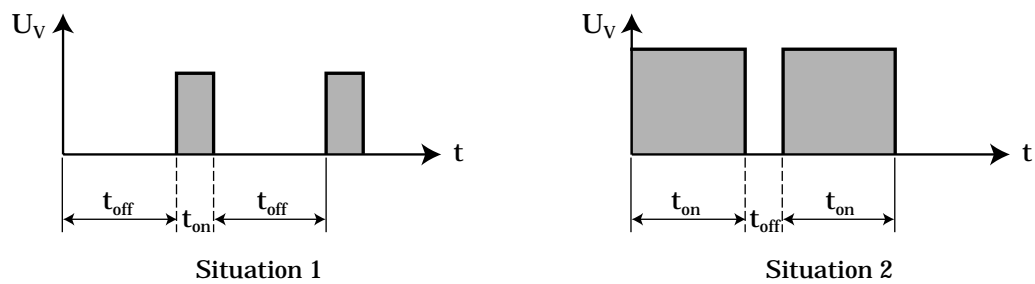
Fig. 2.13   The chopper transistor regulates the intermediate circuit

The filter of the intermediate circuit smoothes the square wave voltage after the chopper. The filter capacitor and coil keep the voltage constant at a given frequency.

The intermediate circuit can also provide a number of additional functions depending on its design, such as:

- decoupling of rectifier from inverter
- reduction of harmonics
- energy storage to contain intermittent load surges.

The inverter

The inverter is the last link in the frequency converter before the motor and the point where the final adaptation of the output voltage occurs.

The frequency converter guarantees good operating conditions throughout the whole control range by adapting the output voltage to the load conditions. It is thus possible to maintain the magnetisation of the motor at the optimal value.

From the intermediate circuit, the inverter either receives
- a variable direct current,
- a variable DC voltage, or
- a constant DC voltage.

In every case, the inverter ensures that the supply to the motor becomes a variable quantity. In other words, the frequency of the motor voltage is always generated in the inverter. If the current or voltage is variable, the inverter only generates the frequency. If the voltage is constant, the inverter generates the motor frequency as well as the voltage.

Even if inverters work in different ways, their basic structure is always the same. The main components are controlled semi-conductors, placed in pairs in three branches.

The thyristors have now largely been replaced by high frequency transistors which can be switched on and off very rapidly. Although this depends on the semi conductor used, it is typically between 300 Hz to 20 kHz.

The semi-conductors in the inverter are turned on and off by signals generated by the control circuit. Signals can be controlled in a number of different ways.
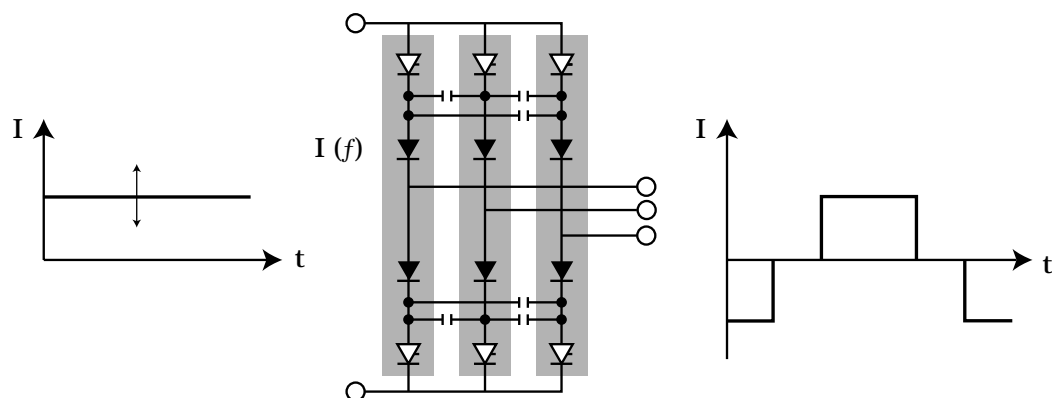
Fig. 2.14   Traditional Inverter for variable voltage intermediate circuit current

In traditional inverters, dealing mainly with variable voltage intermediate current the inverter consists of six diodes, six thyristors and six capacitors.

The capacitors enable the thyristors to switch on and off, so that the current is displaced 120 degrees in the phase windings and must be adapted to the motor size. An intermittent rotational field with the required frequency is produced when the motor terminals are periodically supplied with current in turns U-V, V-W, W-U, U-V..... Even if this makes the motor current almost square, the motor voltage is almost sinusoidal. However, there are always voltage peaks when the current is switched on or off.

The diodes separate the capacitors from the load current of the motor.
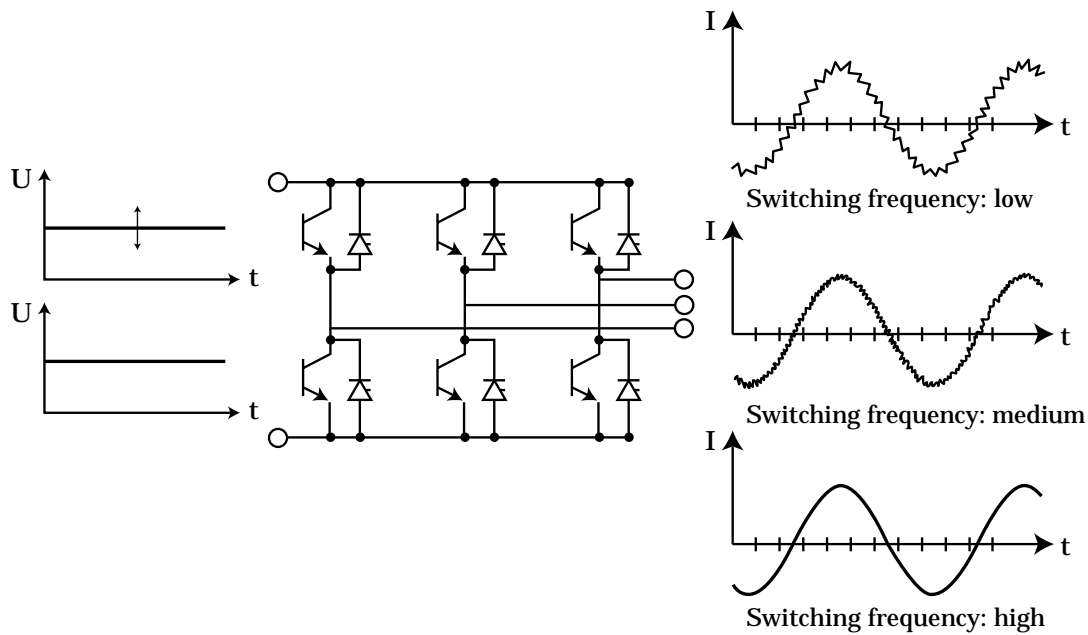
*Fig. 2.15   Inverter for variable or constant intermediate circuit volt-
age and the output current dependent on the switching fre-
quency of the inverter*

In variable or constant intermediate circuit voltage inverters
there are six switching components and regardless of the type of
semi-conductors used, the function is basically the same. The
control circuit switches the semi-conductors on and off using a
number of different modulation techniques, thus changing the
output frequency of the frequency converter.

The first technique deals with variable voltage or current in the
intermediate circuit.

The intervals during which the individual semi-conductors are
conducting are placed in a sequence which is used to obtain the
required output frequency.

This semi-conductor switching sequence is controlled by the size
of the intermediate circuit variable voltage, or current. Using a
voltage-controlled oscillator, the frequency always follows the
amplitude of the voltage. This type of inverter control is called
Pulse Amplitude Modulation (PAM).

The other main technique uses a fixed intermediate circuit volt-
age. The motor voltage is made variable by applying the inter-
mediate circuit voltage to the motor windings for longer or
shorter periods of time.
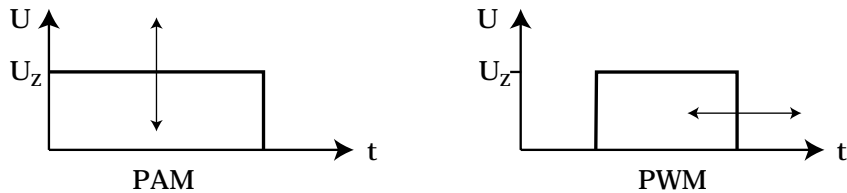
Fig. 2.16   Modulation of amplitude and pulse width

The frequency is changed by varying the voltage pulses along the time axis – positively for one half-period and negatively for the other.

As the technique changes the width of the voltage pulses, it is called Pulse-Width-Modulation or PWM. PWM (and related techniques such as sine-controlled PWM) is the most common technique for inverter control.

In PWM techniques the control circuit determines the on and off switching times of the semi-conductors at the intersection between a delta voltage and a superimposed, sinusoidal reference voltage (sine-controlled PWM).
Other advanced PWM technique includes modified PWM such as Danfoss's VVC and VVC[plus].

These two principles are described from page 82.

Transistors

As transistors can be switched at high speeds, the magnetic noise generated by the "pulse" magnetisation of the motor is reduced.

Another advantage of the high switching frequency is the flexible modulation of the output voltage of the frequency converter which enables a sinusoidal motor current to be generated as the control circuit only has to switch the inverter transistors off and on.
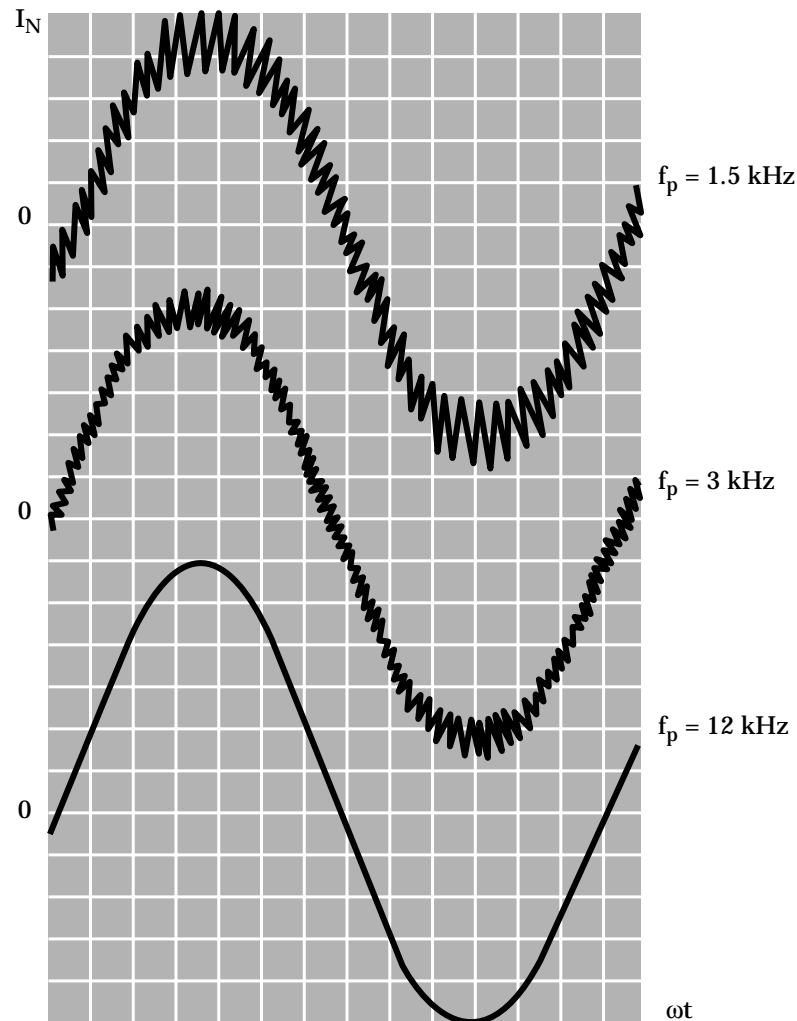
Fig. 2.17   Switching frequency influence of the motor current

The inverter switching frequency is a balancing act as high frequencies can lead to motor heating and high peak voltages. The higher the switching frequency the higher the losses.

On the other hand low switching frequency can lead to high acoustic motor noise.

High-frequency transistors can be divided into three main types:
• Bipolar (LTR)
• Unipolar (MOS-FET)
• Insulated-Gate-Bipolar (IGBT)

Today IGBT transistors are the most widely used as they combine the control properties of the MOS-FET transistors with the output properties of the LTR transistors and have the right power range, conductivity, switching frequency and ease of control for modern frequency converters.

With IGBT transistors both the inverter components and its controls are placed in a moulded module, called the "Intelligent Power Module" (IPM).

The table below gives the major differences between MOS-FET, IGBT and LTR.
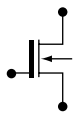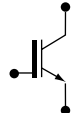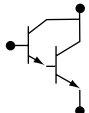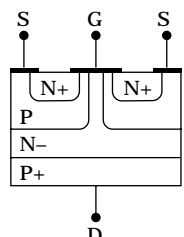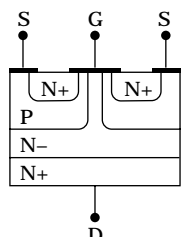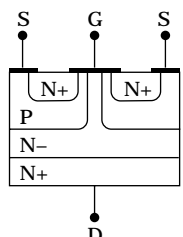
Semi-conductor Properties	MOS-FET	IGBT	LTR
Symbol			
Design			
Conductivity Current conductivity Losses	Low High	High Insignificant	High Insignificant
Blocking conditions Upper limit	Low	High	Medium
Switching conditions Turn-on time Turn-off time Losses	Short Short Insignificant	Medium Medium Medium	Medium Low Groß
Control conditions Power Driver	Low Voltage	Low Voltage	High Current

Fig. 2.18   Comparison of power transistors
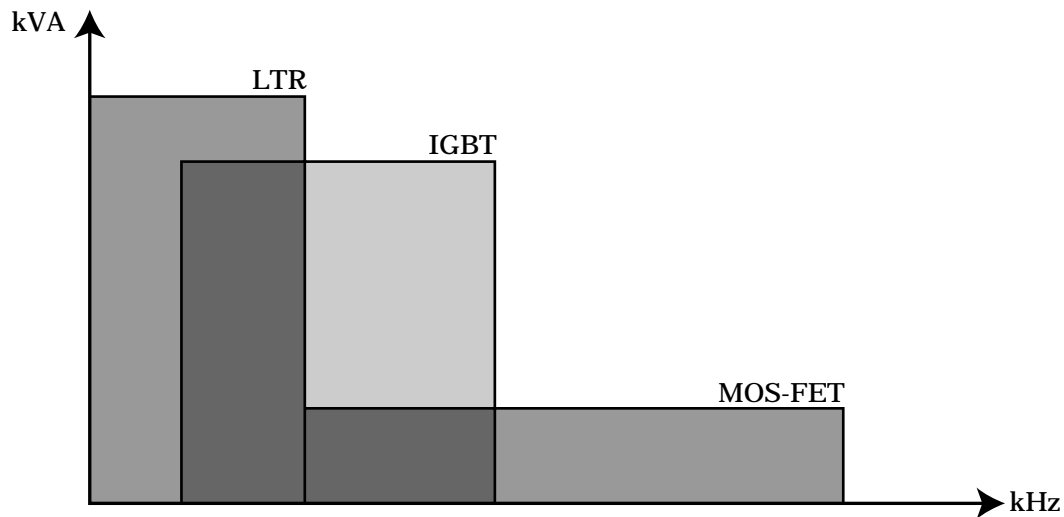
Fig. 2.19   Power and frequency range of power transistors

Pulse-Amplitude-Modulation (PAM)

PAM is used for frequency converters with variable intermediate circuit voltage.

In frequency converters with uncontrolled rectifiers the amplitude of the output voltage is generated by the intermediate circuit chopper and where the rectifier is controlled, the amplitude is generated directly.
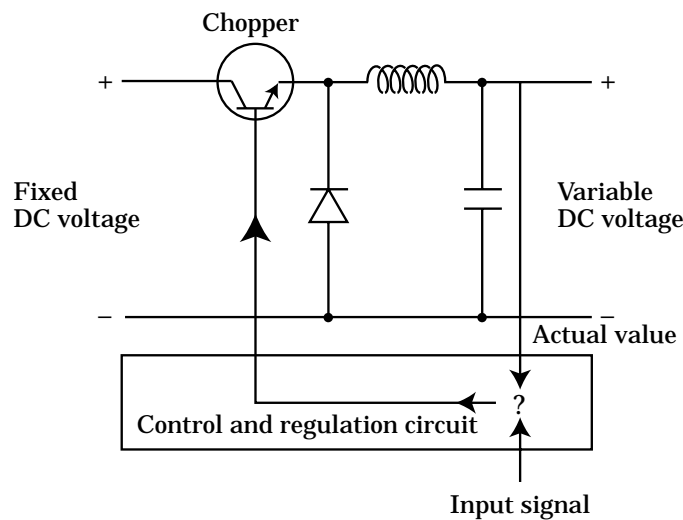
Fig. 2.20   Voltage generation in frequency converters with intermediate circuit chopper

The transistor (chopper) in Fig. 2.20 is switched on or off by the control and regulation circuit. The switching times depend on the rated value (input signal) and the measured (actual value) voltage signal. The actual value is measured at the capacitor.

Both the coil and capacitor act as a filter that smoothes the voltage ripple. The voltage peak depends on the opening times of the transistor and if the rated value and actual value differ, the chopper is regulated until the required voltage level is reached.

Frequency Control

The output voltage frequency is varied by the inverter during the change of period and during the periods the semi-conductor switching units are activated a number of times.

The period length can be controlled is two ways:
1. directly by the input signal, or
2. by the variable DC voltage which is proportional to the input signal.
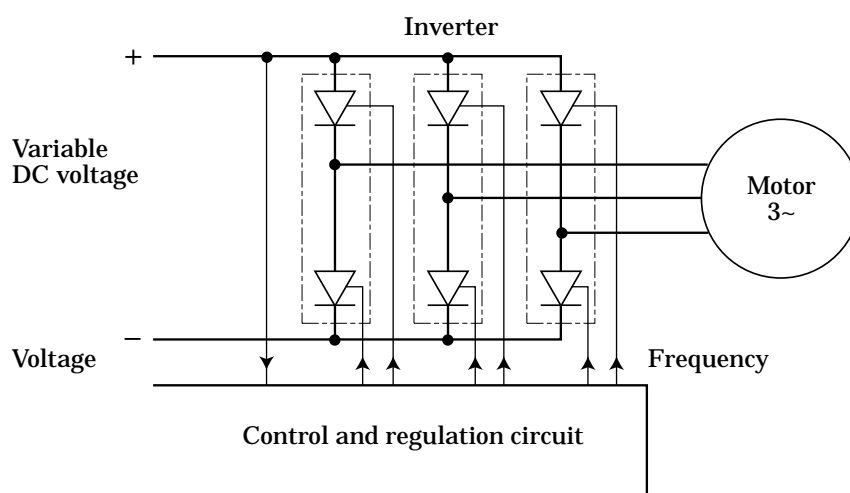
Fig. 2.21a Frequency control via intermediate circuit voltage

Pulse-Width-Modulation (PWM)

PWM is the most widely used procedure for generating a three-phase voltage with corresponding frequency.

With PWM the full intermediate circuit voltage ($\approx \sqrt{2} \times U_{mains}$) is switched on or off by the power electronic components. The pulse-width repetition rate between the on and off switching times is variable and causes the voltage adjustment.

There are 3 main options for determining the switching patterns in an PWM controlled inverter.
1. Sine controlled PWM
2. Synchronous PWM
3. Asynchronous PWM

Each inverter branch of a three-phase PWM inverter can have two different positions (on or off).
The three switches generate eight possible switching combinations (2^3) and, therefore eight discrete voltage vectors at the output of the inverter or at the stator winding of the connected motor. As shown in Fig. 2.21b, these vectors 100, 110, 010, 011, 001, 101 are placed at the corners of a suspended hexagon, using 000 and 111 as zero vectors.
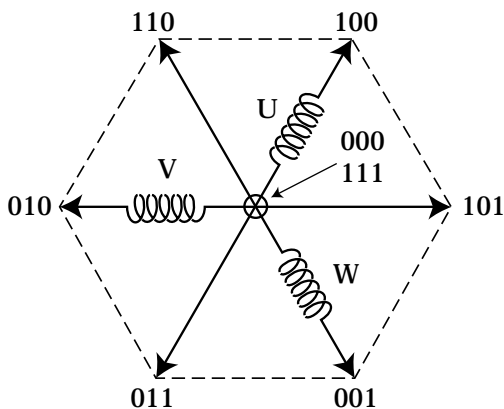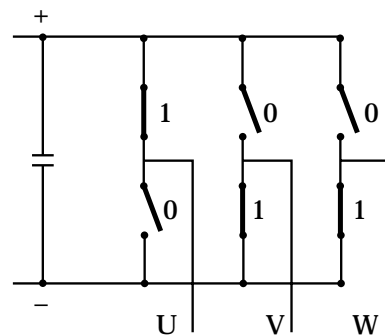
Fig. 2.21b   Fig. 2.21c

With switching combinations 000 and 111, the same potential is generated at all three output terminals of the inverter – either a plus or minus potential from the intermediate circuit (see Fig. 2.21c). For the motor, this comes close to the effect of a terminal short-circuit; the 0 V voltage is also impressed on the motor windings.

Sine-controlled PWM

In sine controlled PWM the control principle uses a sinusoidal reference voltage (U_s) for each inverter output. The period length of the sinusoidal voltage corresponds to the required basic frequency of the output voltage. The three reference voltages are superimposed by a delta voltage (U_Δ) (see Fig. 2.22).
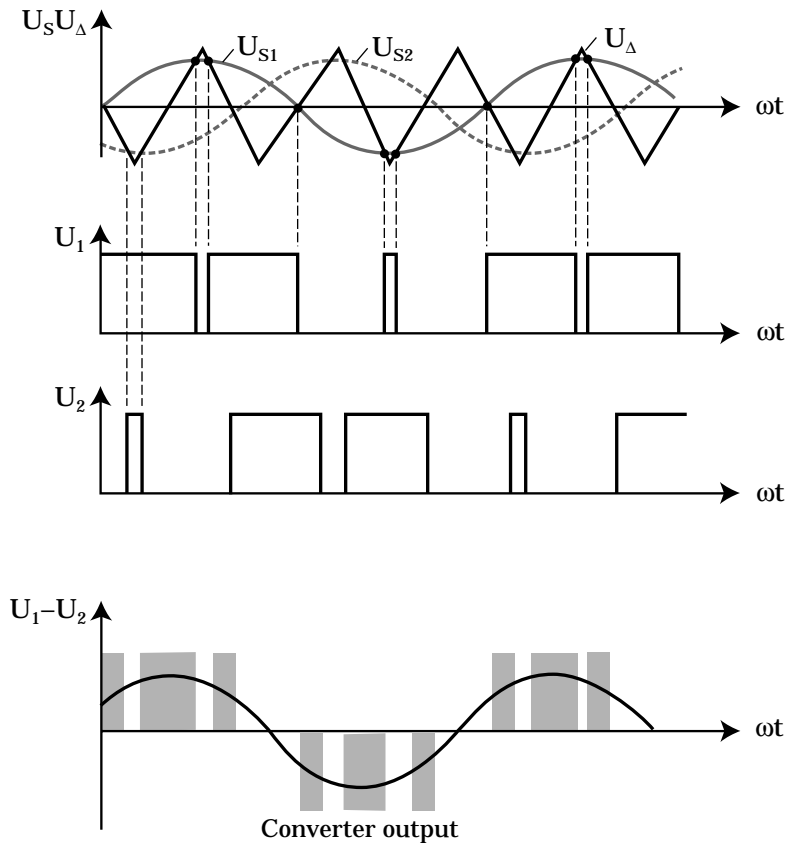
Fig. 2.22   Principle of the sine-controlled PWM (with two reference voltages)

At the intersection of the delta voltage and the sine references, the inverters semi-conductors are either turned on or off.

The intersections are determined electronically by the control card. If the delta voltage is higher than the sine voltage, the output pulse changes from positive to negative (or negative to positive) when the delta voltage is reduced, so the maximum output voltage of the frequency converter is determined by the intermediate circuit voltage.

The output voltage is changed by the ratio between the on and off time and this ratio can be changed to generate the required voltage. The amplitude of the negative and positive voltage pulses thus always corresponds to half the intermediate circuit voltage.
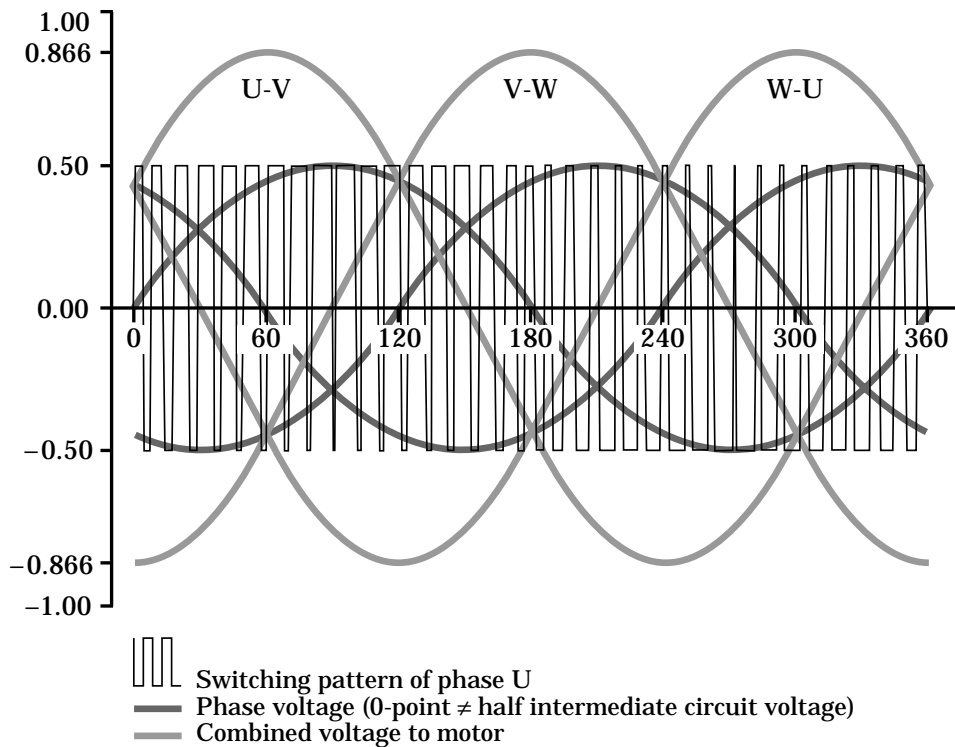
Fig. 2.23   Output voltage of sine-controlled PWM

At low stator frequencies, the "off" time increases and may become so big that it is not possible to maintain the frequency of the delta voltage.

This makes the voltage-free period too long causing the motor to run irregularly. In order to avoid this, the frequency of the delta voltage can be doubled at low frequencies.

The phase voltage of the frequency inverter output terminals corresponds to half the intermediate circuit voltage divided by $\sqrt{2}$ and is thus equal to half the mains supply voltage. The mains voltage of the output terminals is equal to $\sqrt{3}$ times the phase voltage and is thus equal to 0.866 times the mains supply voltage.

A PWM controlled inverter which works exclusively with sinusoidal reference modulation can deliver up to 86.6% of the rated voltage (see figure 2.23).

The output voltage of the frequency converter cannot reach the motor voltage using just sine modulation, as the output voltage will be approximately 13% too low.

However, the extra voltage needed can be obtained by reducing the pulse number when the frequency exceeds about 45 Hz – but there are some drawbacks with this technique. In particular it makes the voltage alternate step-wise and the motor current becomes unstable. If the number of pulses is reduced, the over-harmonics at the frequency converter output increases, leading to higher losses in the motor.

Another way of dealing with the problem involves using other reference voltages in place of the three sine references. These could be any shape of waveform (eg, trapeze-shaped or step-shaped).

For example one common reference voltage uses the 3rd harmonic of the sine reference. By increasing the amplitude of the sine reference by 15.5% and adding the 3rd harmonic, a switching pattern for the inverters semi-conductor can be obtained which increases the output voltage of the frequency converter.

Synchronous PWM

A basic problem of the sine controlled PWM procedure lies in determining the optimum switching times and angle for the voltage over a given period. These switching times must be set to allow only a minimum of upper harmonic waves. Such a switching pattern is only maintained for a given (limited) frequency range. Operation outside this range requires another switching pattern.

Using sine controlled PWM it is necessary to optimise the voltage utilisation and minimise the harmonic spectrum. If the repetition rate (i.e. the frequency of the delta voltage) becomes very high in relation to the frequency of the reference signal, these two signals may run asynchronously in relation to each other. At frequency ratios close to 10 or lower, disturbing harmonics will occur and it becomes necessary to synchronise the two signals. This synchronisation can be seen from the so-called "gearshift" which is good for three-phase AC drives with low dynamic properties, where voltage and frequency (normal V/f control) can be changed slowly.

Asynchronous PWM

The demand for field-orientation and fast system reaction for torque and speed control of three-phase AC drives (excluding servo-drives) requires a stepwise modification of the amplitude and angle of the inverter voltage. Using a "normal" or "synchronous" PWM switching pattern, it is not possible to change the amplitude and angle of the inverter voltage step-wise.

However, one way of meeting this requirement is the asynchronous PWM procedure, in which instead of synchronising the modulation of the output voltage to the output frequency, as is normally done to reduce harmonics in the motor, the modulation is fed to the voltage vector control cycle – this results in an asynchronous relationship to the output frequency.

There are two main asynchronous PWM techniques:
- SFAVM (**S**tator **F**low-oriented **A**synchronous **V**ector **M**odulation)
- 60° AVM (**A**synchronous **V**ector **M**odulation).

SFAVM

SFAVM is a space-vector modulation procedure that makes it possible to change the inverter voltage, amplitude and angle at random, but stepwise within the switching time (in other words asynchronously). This gives better dynamic performance.

The main objective of this modulation is to optimise the stator flux using the stator voltage whilst minimising torque ripple, as the deviation of the angle depends on the switching sequence and can lead to a higher torque ripple. Consequently, the switching sequence must be calculated so as to ensure that the deviation of the vector angle is minimised. Switching between the voltage vectors is based on a calculation of the desired trajectory of the motors stator flux, which in turn determines the airgap torque.

Previously, conventional PWM supply suffered from a deviation of the stator flux vector amplitude and the flux angle. These deviations affected the rotating field (torque) in the air gap of the motor and caused a torque ripple. The effect of the amplitude deviation is insignificantly small and can be further reduced by increasing the switching frequency.

Generation of motor voltage

Stationary operation, corresponds to controlling the machine voltage vector $U_{\omega t}$ to a circular trajectory, as shown in Fig. 2.24.

The length of the voltage vector is a measure of the value of the motor voltage and the speed of rotation and corresponds to the operating frequency at the time in question. The motor voltage is generated through the formation of average values by means of short pulses from adjacent vectors.

The Danfoss SFAVM has among others the following properties:

- The voltage vector can be controlled without deviation with respect to the preset reference, in amplitude and angle.

- A switching sequence which always begins from 000 or 111. This enables each voltage vector to have three switching modes.

- A mean value of the voltage vector is obtained by short pulses of adjacent vectors as well as zero vectors 000 and 111.

Generation of motor voltage can be explained in more detail by means of the following examples, illustrated in 2.24 and 2.25:
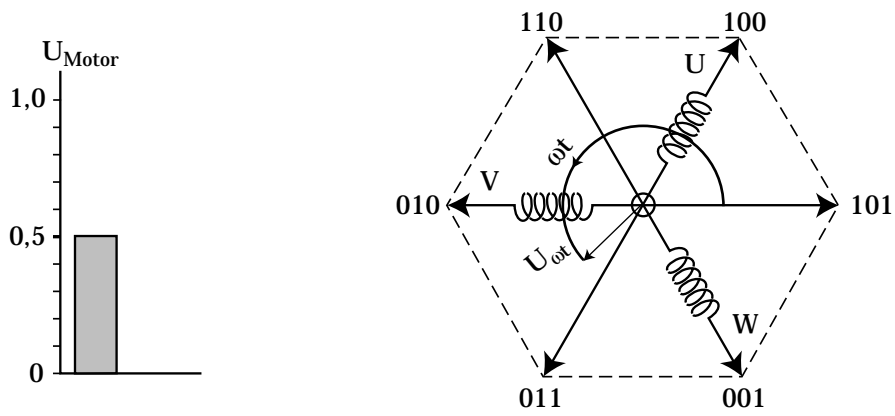
a) *Present output voltage 50% of rated voltage)*

b) *Subsequent generation of the ideal voltage vector U_{ax} through PWM between adjacent, adjustable voltage vectors*
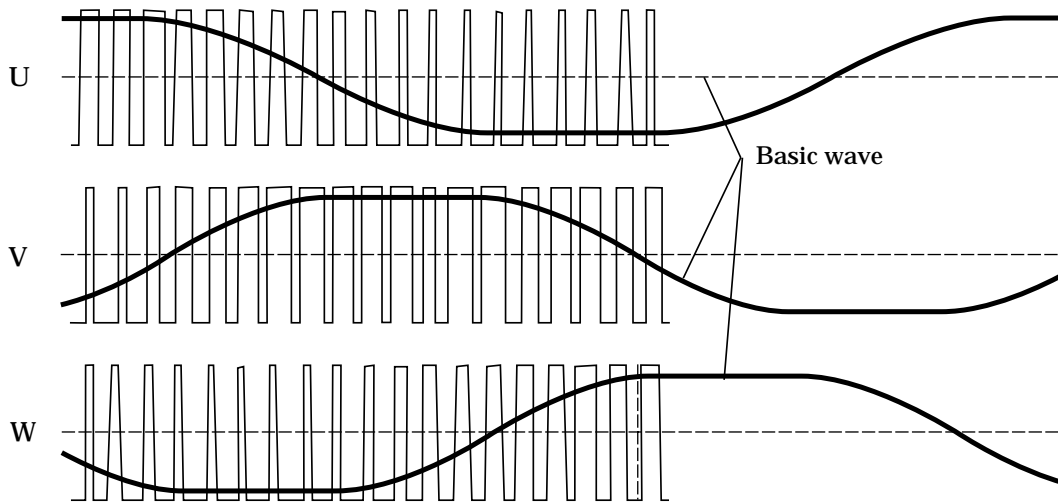
c) *Time sequence of the control signals for the three inverter phases – U, V, W*

Fig. 2.24   *Momentary recording of torque PWM based on the space vector modulation (SFAVM) for 50% rated motor voltage*

The preset reference value ($U_{\omega t}$) in Fig. 2.24a is 50%. The output voltage is generated through short pulses of the adjacent vector – in this case 011 and 001, as well as 000 and 111 – in the form of a mean value (Fig. 2.24b).

Fig. 2.25 shows the generation of a motor voltage of 100%.

a) *Preset output voltage (100% of rated voltage)*

b) *Generation of the ideal voltage vector $U_{\omega t}$ through PWM between adjacent, adjustable voltage vectors*
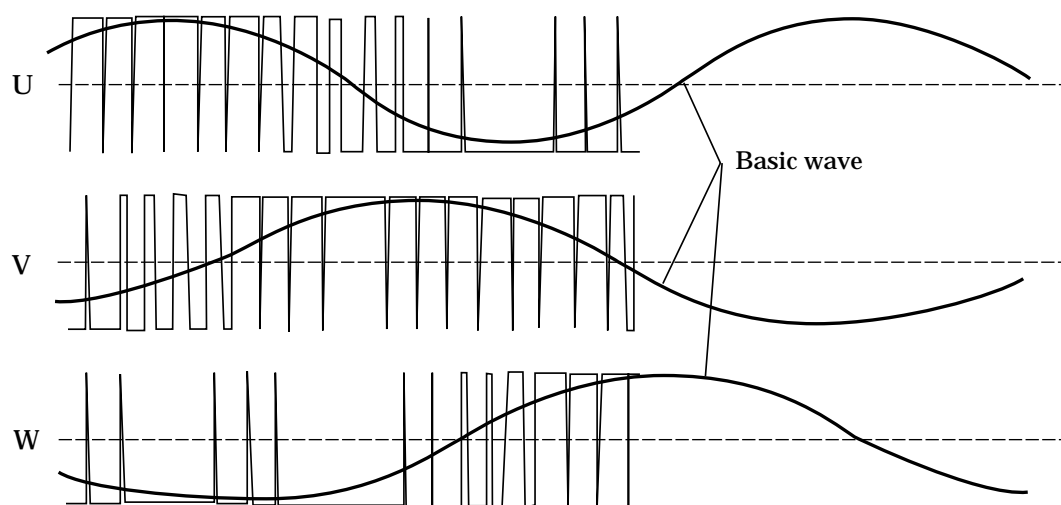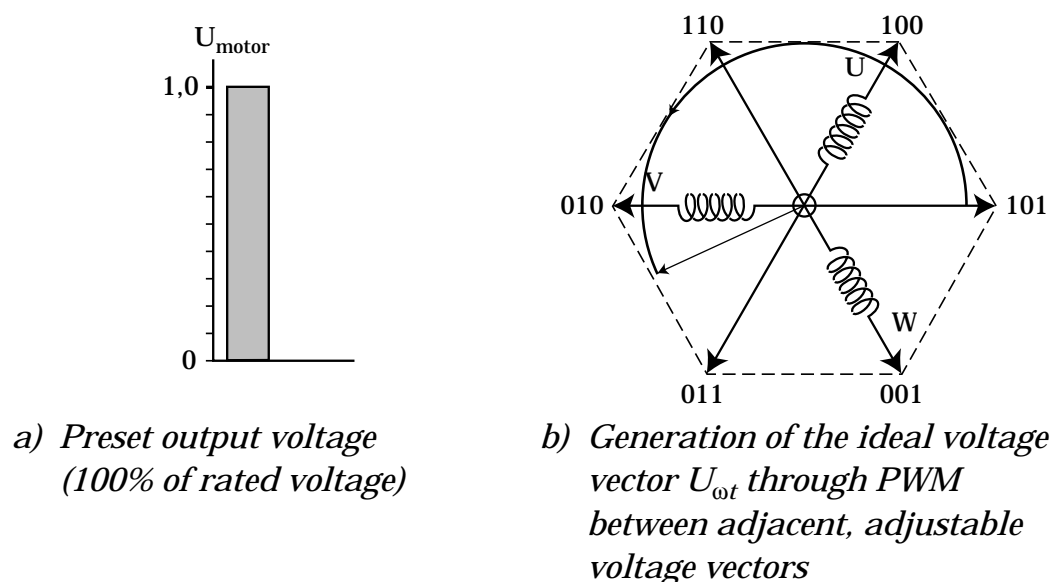
c) *Time sequence of the control signals for three inverter phases – U, V, W*

Fig. 2.25 *Momentary recording of torque PWM based on space vector modulation (SFAVM) for 100% rated voltage*

SFAVM creates a connection between control system and the power circuit of the inverter. The modulation is synchronous to the control frequency of the controls (see chapter VVC[plus]) and asynchronous to the basic frequency of the motor voltage.

Synchronisation between control and modulation is an advantage for the high-power controls (voltage vector, flux vector), since the control system of the voltage vector is able to control directly and without limitations (amplitude, angle and angle speed are controllable).

In order to dramatically reduce the "on-line" calculation time, the voltage values for different angles are given in a table. Fig. 2.26 shows an abstract from the vector modulation table for SFAVM as well as the output voltage (to the motor).
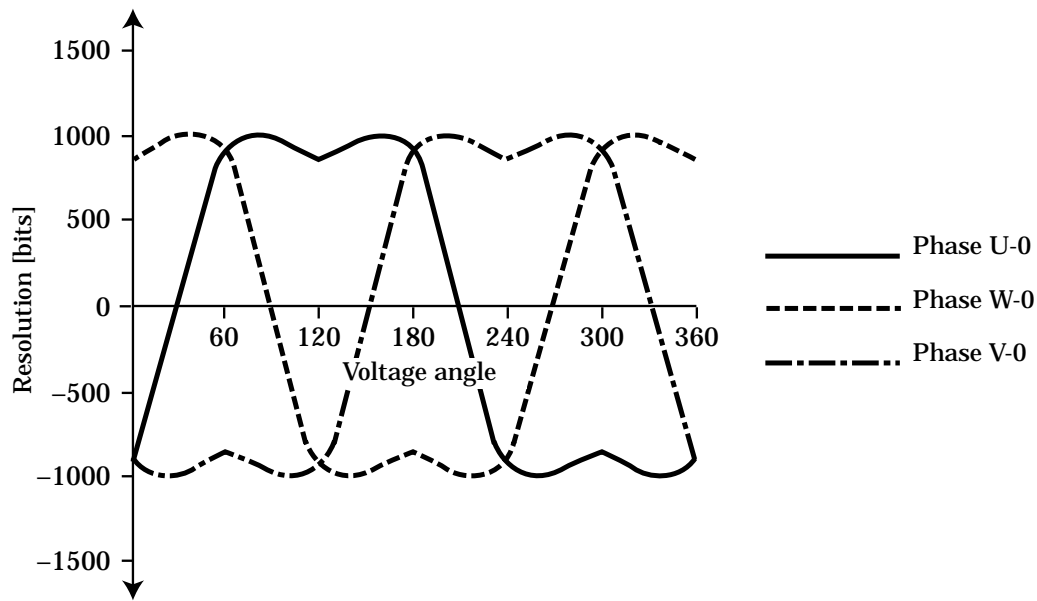
Fig. 2.26   Outputs given in the vector modulation table (SFAVM)
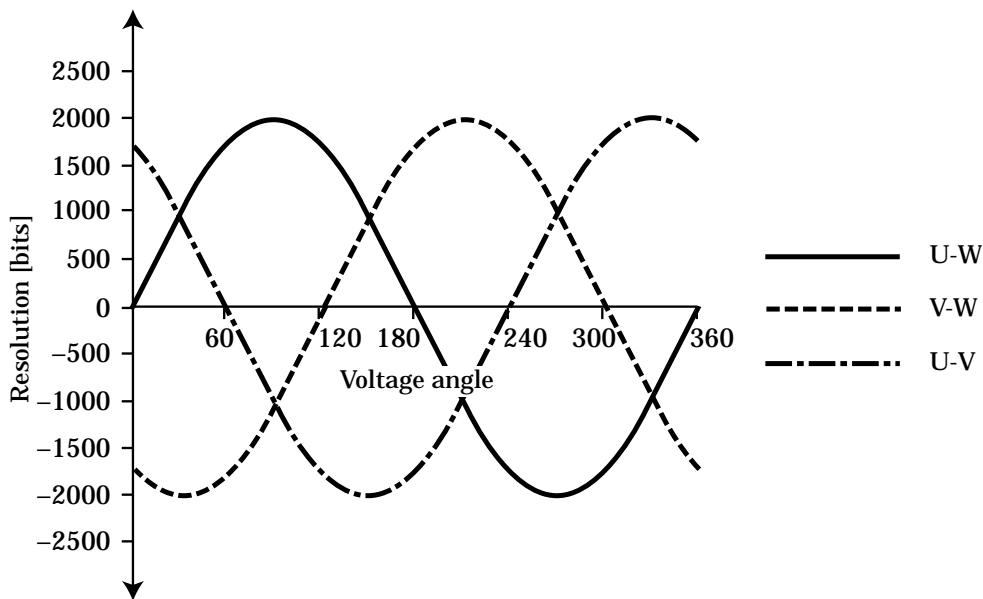
Fig. 2.27   Output voltage (motor) – (phase-phase)

60° AVM

When 60° AVM (Asynchronous Vector Modulation) is used – instead of the SFAVM procedure – the voltage vectors can be determined as follows:

- Within a switching period, only one zero vector (000 or 111) is used.
- A switching sequence does not always begin from a zero vector (000 or 111).
- Within $\frac{1}{6}$ period (60°) the inverter is not switched in one phase. The switch state (0 or 1) is maintained.
  In the two other phases, switching is normal.

Fig. 2.28a/b gives a comparison of the switching sequence in the 60° AVM procedure as against that of the SFAVM procedure – for a short interval (a) and for several periods
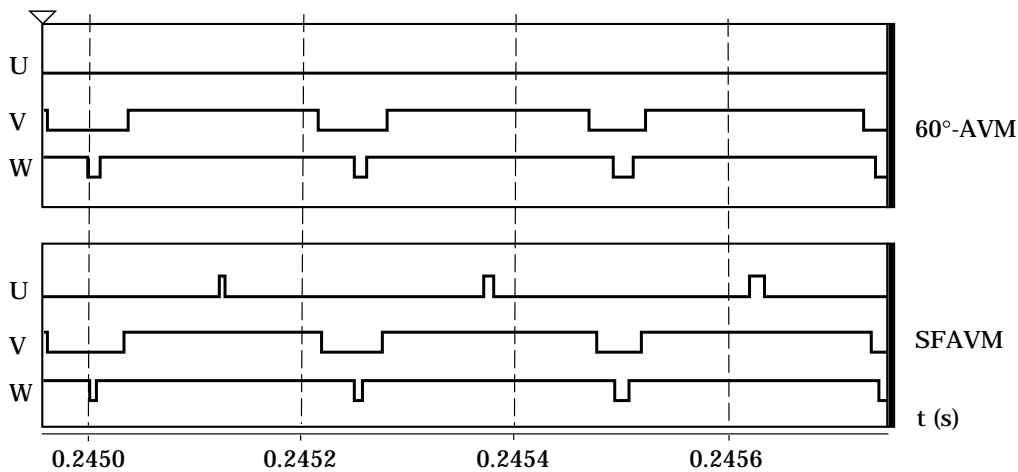
Fig. 2.28a   Switching sequence in 60° AVM and SFAVM for some 60° intervals
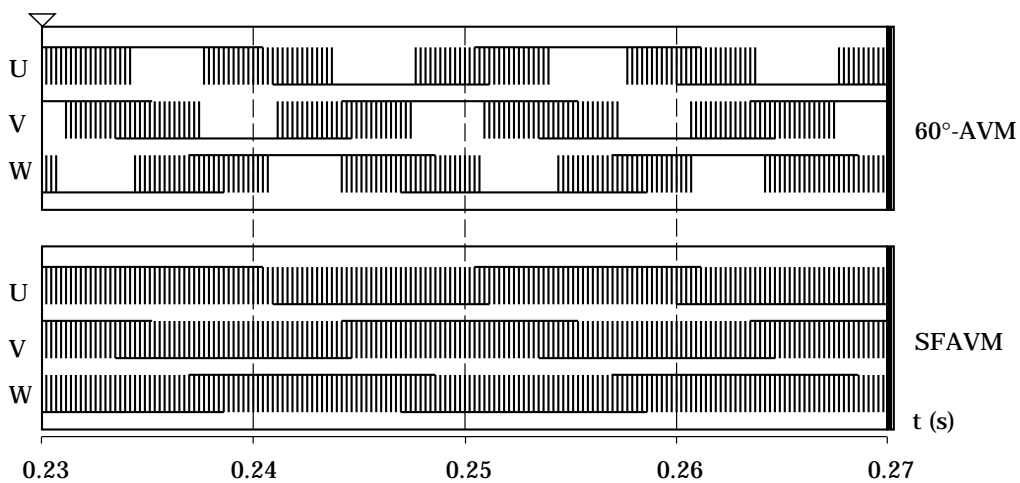
Fig. 2.28b   Switching sequence in 60° AVM and SFAVM, respectively, for several periods

Control circuit

The control circuit, or control card, is the fourth main component of the frequency converter and has four essential tasks:
- control of the frequency converter semi-conductors.
- data exchange between the frequency converter and peripherals.
- gathering and reporting fault messages.
- carrying out of protective functions for the frequency converter and motor.

Micro-processors have increased the speed of the control circuit, significantly increasing the number of applications suitable for drives and reducing the number of necessary calculations.

With microprocessors the processor is integrated into the frequency converter and is always able to determine the optimum pulse pattern for each operating state.

Control circuit for PAM frequency converter

Control circuit for chopper frequency

PI voltage regulator

Sequence generator
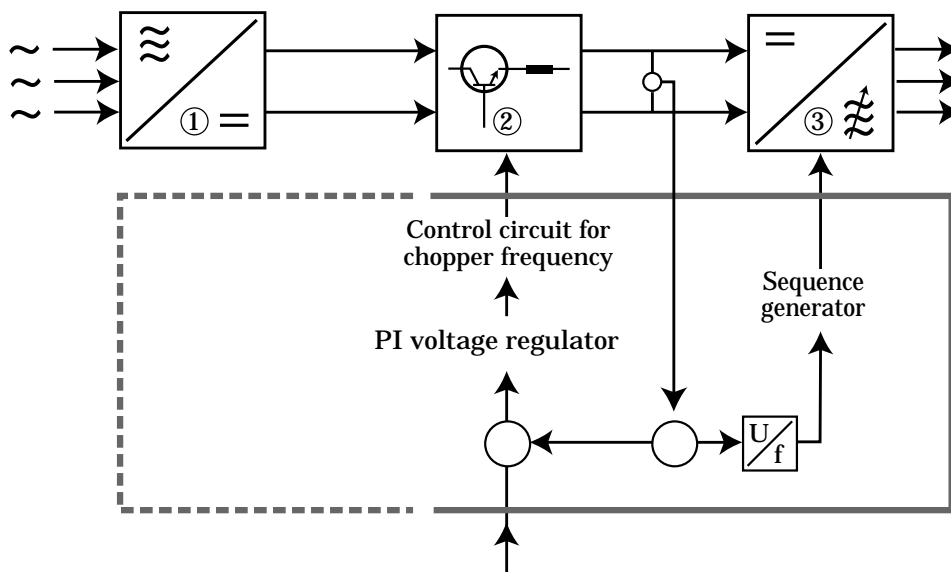
Fig. 2.29   The principle of a control circuit used for a chopper-controlled intermediate circuit

Fig. 2.29 shows a PAM-controlled frequency converter with intermediate circuit chopper. The control circuit controls the chopper (2) and the inverter (3).

This is done in accordance with the momentary value of the intermediate circuit voltage.

The intermediate circuit voltage controls a circuit that functions as an address counter in the data storage. The storage has the output sequences for the pulse pattern of the inverter. When the intermediate circuit voltage increases, the counting goes faster, the sequence is completed faster and the output frequency increases.

With respect to the chopper control, the intermediate circuit voltage is first compared with the rated value of the reference signal – a voltage signal. This voltage signal is expected to give a correct output voltage and frequency. If the reference and intermediate circuit signals vary, a PI-regulator informs a circuit that the cycle time must be changed. This leads to an adjustment of the intermediate circuit voltage to the reference signal.

PAM is the traditional technology for frequency inverter control. PWM is the more modern technique and the following pages detail how Danfoss has adapted PWM to provide particular and specific benefits.

Danfoss control principle

Fig. 2.30 gives the control procedure for Danfoss inverters.
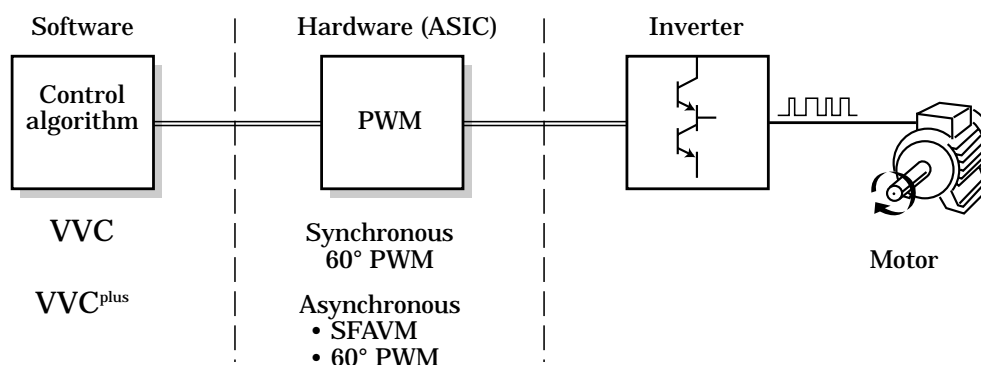
Fig. 2.30   Control principles used by Danfoss

The control algorithm is used to calculate the inverter PWM switching and takes the form of a **V**oltage **V**ector **C**ontrol (**VVC**) for voltage-source frequency converters.

VVC controls the amplitude and frequency of the voltage vector using load and slip compensation. The angle of the voltage vector is determined in relation to the preset motor frequency (reference) as well as the switching frequency. This provides:

- full rated motor voltage at rated motor frequency (so there is no need for power reduction)
- speed regulation range: 1:25 without feedback
- speed accuracy: ±1% of rated speed without feedback
- robust against load changes

A recent development of VVC is VVC^{plus} under which. The amplitude and angle of the voltage vector, as well as the frequency, is directly controlled.

In addition to the properties of VVC , VVC^{plus} provides:
- improved dynamic properties in the low speed range (0 Hz-10 Hz).
- improved motor magnetisation
- speed control range: 1:100 without feedback
- speed accuracy: ±0.5% of the rated speed without feedback
- active resonance dampening
- torque control (open loop)
- operation at the current limit

VVC control principle

Under VVC the control circuit applies a mathematical model, which calculates the optimum motor magnetisation at varying motor loads using compensation parameters.

In addition the synchronous 60° PWM procedure, which is integrated into an ASIC circuit, determines the optimum switching times for the semi-conductors (IGBTs) of the inverter.

The switching times are determined when:
• The numerically largest phase is kept at its positive or negative potential for $\frac{1}{6}$ of the period time (60°).
• The two other phases are varied proportionally so that the resulting output voltage (phase-phase) is again sinusoidal and reaches the desired amplitude (Fig. 2.32).

U_{DC} = intermediate circuit voltage
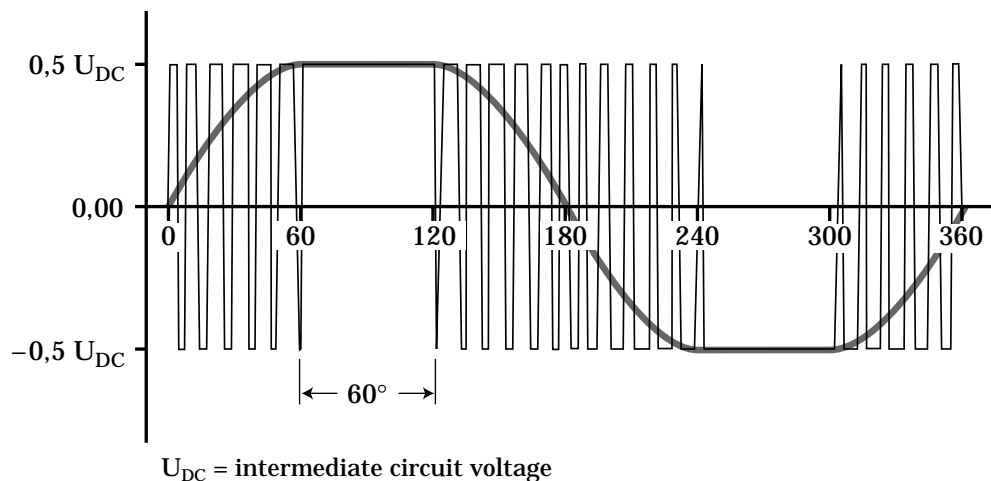
Fig. 2.31   Synchronous 60° PWM (Danfoss VVC control) of one phase

Unlike sine-controlled PWM, VVC is based on a digital genera-
tion of the required output voltage. This ensures that the fre-
quency converter output reaches the rated value of the supply
voltage, the motor current becomes sinusoidal and the motor
operation corresponds to those obtained in direct mains connec-
tion.
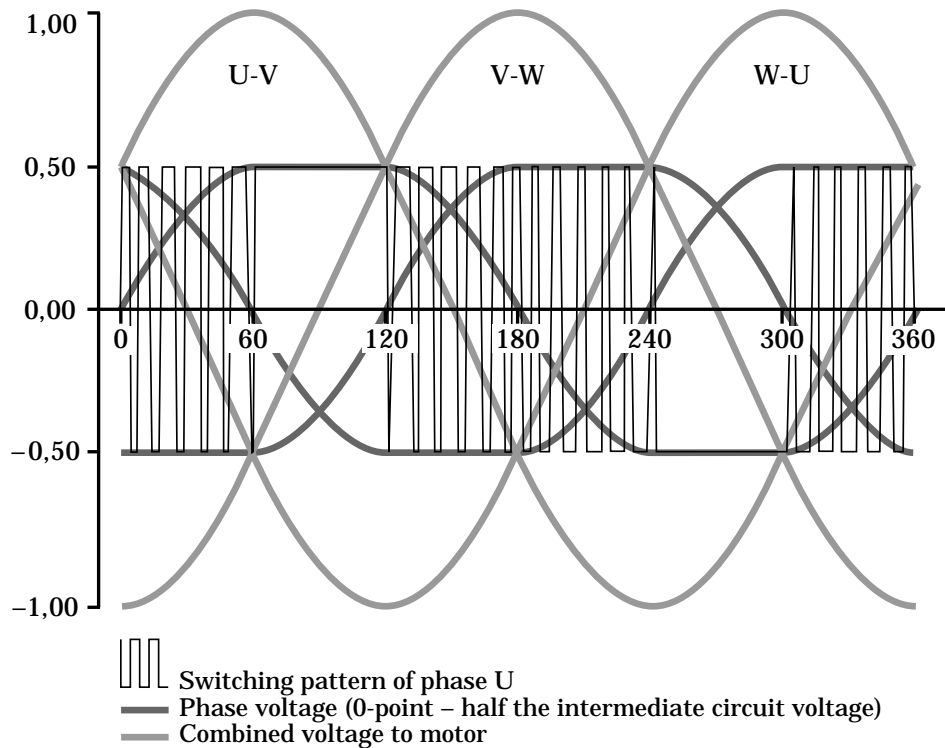
Fig. 2.32   *With the synchronous 60° PWM principle the full output*
              voltage is obtained directly

Optimum motor magnetisation is obtained because the fre-
quency converter takes the motor constants (stator resistance
and inductance) into account when calculating the optimum
output voltage.

As the frequency converter continues to measure the load cur-
rent, it can regulate the output voltage to match the load, so the
motor voltage is adapted to the motor type and follows load con-
ditions.

VVC^{plus} control principle

The VVC^{plus} control principle uses a vector modulation principle for constant, voltage-sourced PWM inverters. It is based on an improved motor model which makes for better load and slip compensation, because both the active and the reactive current components are available to the control system and controlling the voltage vector angle significantly improves dynamic performance in the 0-10 Hz range where standard PWM U/F drives typically have problems.

The inverter switching pattern is calculated using either the SFAVM or 60° AVM principle, to keep the pulsating torque in the air gap very small (compared to frequency converters using synchronous PWM).

The user can select his preferred operating principle, or allow the inverter to choose automatically on the basis of the heat-sink temperature. If the temperature is below 75°C, the SFAVM principle is used for control, while above 75° the 60° AVM principle is applied.

Table 2.01 gives a brief overview of the two principles:

Selection	Max. switching frequency of inverter	Properties
SFAVM	Max. 8 kHz	1. low torque ripple compared to the synchronous 60° PWM (VVC) 2. no "gearshift" 3. high switching losses in inverter
60°-AVM	Max. 14 kHz	1. reduced switching losses in inverter (by $^1/_3$ compared to SFAVM) 2. low torque ripple compared to the synchronous 60° PWM (VVC) 3. relatively high torque ripple compared to SFAVM

Table 2.01   Overview: SFAVM versus 60° AVM

The control principle is explained using the equivalent circuit diagram (Fig. 2.33) and the basic control diagram (Fig. 2.34).

It is important to remember that in the no-load state, no current flows in the rotor ($i_\omega = 0$), which means that the no-load voltage can be expressed as:

$$\underline{U} = \underline{U}_L = (R_S + j\omega_S L_S) \times i_s$$
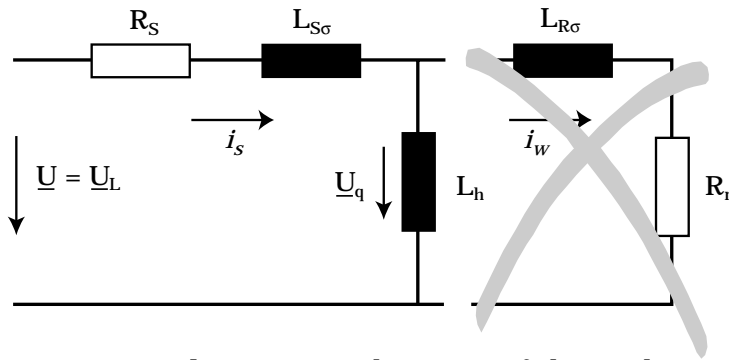
*Fig. 2.33a   Equivalent circuit diagram of three-phase AC motor
loaded)*

in which:
R_S is the stator resistance,
i_s is the motor magnetisation current,
$L_{S\sigma}$ is the stator leakage inductance,
L_h is the main inductance,
L_S $(=L_{S\sigma} + L_h)$ is the stator inductance, and
ω_s $(=2\pi f_s)$ is the angular speed of the rotating field in the air gap
The no-load voltage $(\underline{U}_L)$ is determined by using the motor data (rated voltage, current, frequency, speed).

Under a load, the active current (i_w) flows in the rotor. In order to enable this current, an additional voltage $(\underline{U}_{Comp})$ is placed at the disposal of the motor:
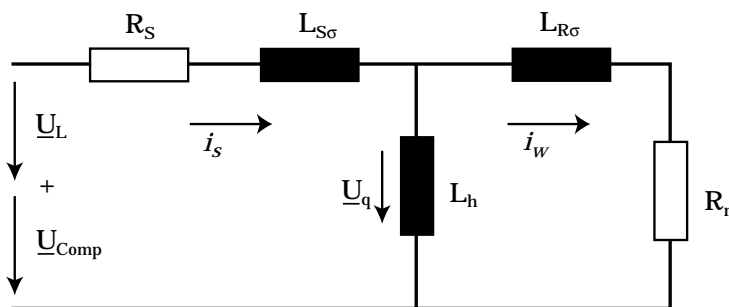
*Fig. 2.33b   Equivalent circuit diagram for three-phase AC motors
(loaded)*

The additional voltage $\underline{U}_{Comp}$ is determined using the no-load and active currents as well as the speed range (low or high speed). The voltage value and the speed range are then determined on the basis of the motor data.

f	frequency (internal)		U_{DC}	voltage of DC intermediate circuit
f_s	preset reference frequency		$\underline{U}_L$	no-load voltage vector
Δ_f	calculated slip frequency		$\underline{U}_S$	stator voltage vector
I_{SX}	reactive current components (calculated)		$\underline{U}_{Comp}$	load-dependent voltage compensation
I_{SY}	active current components (calculated)		U	motor supply voltage
I_{SX0}, I_{SY0}	no-load current of x and y axes (calculated)		X_h	reactance
I_u, I_v, I_w	current of phases U, V and W (measured)		X_1	stator leakage reactance
R_s	stator resistance		X_2	rotor leakage reactance
R_r	rotor resistance		ω_s	stator frequency
θ	angle of the voltage vectors		L_S	stator inductance
θ_0	no-load value theta		L_{Ss}	stator leakage inductance
$\Delta\theta$	load-dependent part of theta (compensation)		L_{Rs}	rotor leakage inductance
T_C	Temperature of heat conductor/ heat sink		i_s	motor phase current (apparent current)
			i_w	active (rotor) current

Explanations for Fig. 2.33 (page 87) and Fig. 2.34 (page 89)
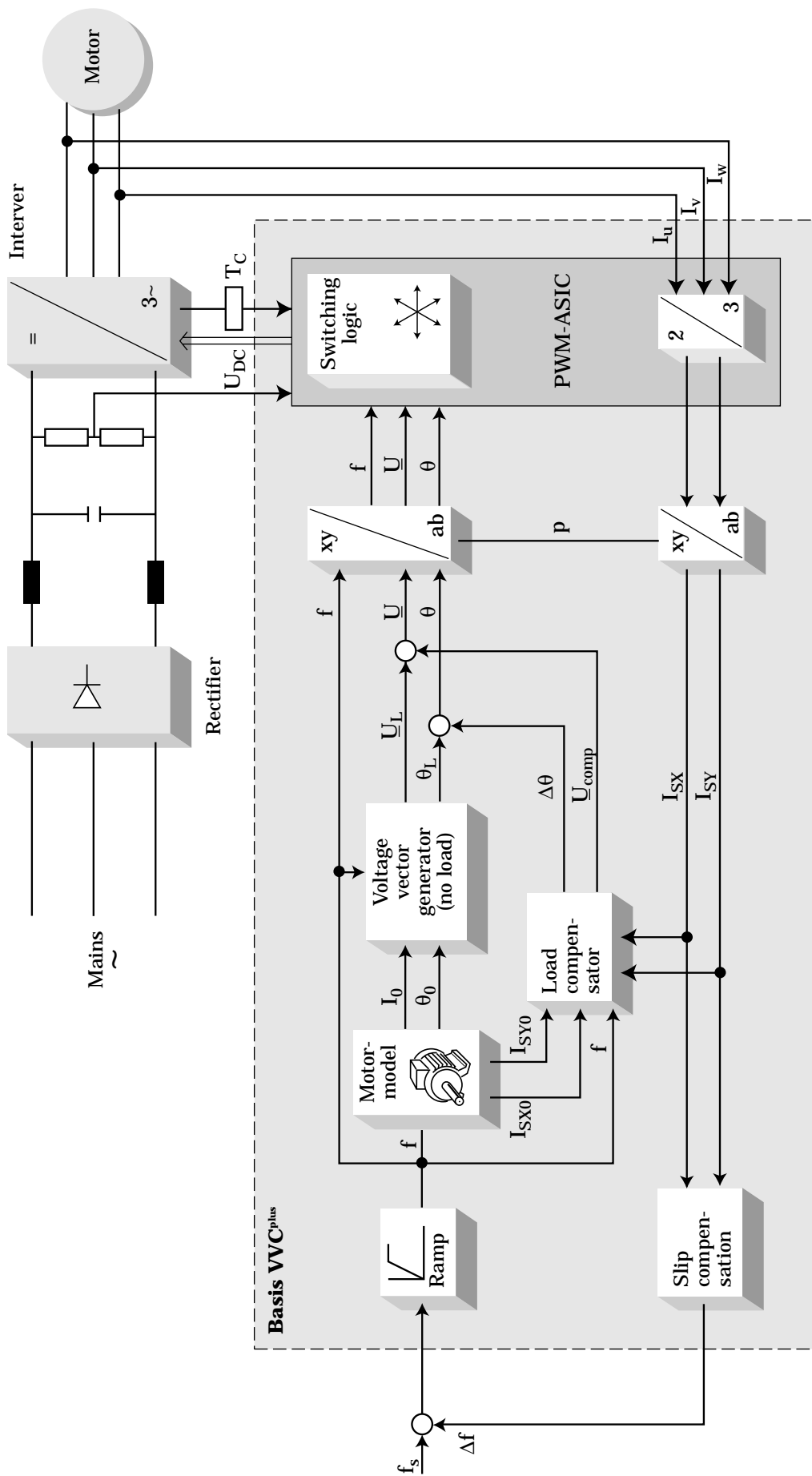
Fig. 2.34   Basis of VVC^plus control

As shown in Fig. 2.34, the motor model calculates the rated no-load values (currents and angles) for the load compensator (I_{SX0}, I_{syo}) and the voltage vector generator (I_o, θ_o). Knowing the actual no load values makes it possible to estimate the motor shaft torque load much more accurately.

The voltage vector generator calculates the no-load voltage vector ($\underline{U}_L$) and the angle (θ_L) of the voltage vector on the basis of the stator frequency, no-load current, stator resistance and inductance (see Fig. 2.33a). The resulting voltage vector amplitude is a composite value having added start voltage and load compensation voltage. The voltage vector θ_L is the sum of four terms, and is an absolute value defining the angular position of the voltage vector.

As the resolution of the theta components (θ) and the stator frequency (F) determines the output frequency resolution, the values are represented in 32 bit resolution. One (θ) theta component is the no load angle which is included in order to improve the voltage vector angle control during acceleration at low speed. This results in a good control of the current vector since the torque current will only have a magnitude which corresponds to the actual load. Without the no load angle component the current vector would tend to increase and over magnetise the motor without producing torque.

The measured motor currents (I_u, I_v and I_w) are used to calculate the reactive current (I_{SX}) and active current (I_{SY}) components.

Based on the calculated actual currents and the values of the voltage vector, the load compensator estimates the air gap torque and calculates how much extra voltage (U_{Comp}) is required to maintain the magnetic field level at the rated value. The angle deviation ($\Delta\theta$) to be expected because of the load on the motor shaft is corrected. The output voltage vector is represented in polar form (p). This enables a direct overmodulation and facilitates the linkage to the PWM-ASIC.

The voltage vector control is very beneficial for low speeds, where the dynamic performance of the drive can be significantly improved, compared to V/f control by appropriate control of the voltage vector angle. In addition, steady stator performance is obtained, since the control system can make better estimates for the load torque, given the vector values for both voltage and current, than is the case on the basis of the scalar signals (amplitude values).

Field-oriented (Vector) control

Vector control can be designed in a number of ways. The major difference is the criteria by which the active current, magnetising current (flux) and torque values are calculated.

Comparing a DC motor and three-phase asynchronous motor (Fig. 2.35), highlights the problems. In the DC, the values that are important for generating torque – flux (Φ) and armature current – are fixed with respect to size and phase position, based on the orientation of the field windings and the position of the carbon brushes (Fig. 2.35a).

In a DC motor the armature current and flux-generating current are at right angles and neither value is very high. In an asynchronous motor the position of the flux (Φ) and the rotor current I_1 depends on the load. Furthermore unlike a DC motor, the phase angles and current are not directly measurable from the size of the stator.

$$M \sim I \times \Phi \times \sin\text{ß}_G$$

DC machine

Simplified vector diagram of asynchronous machine for one load point
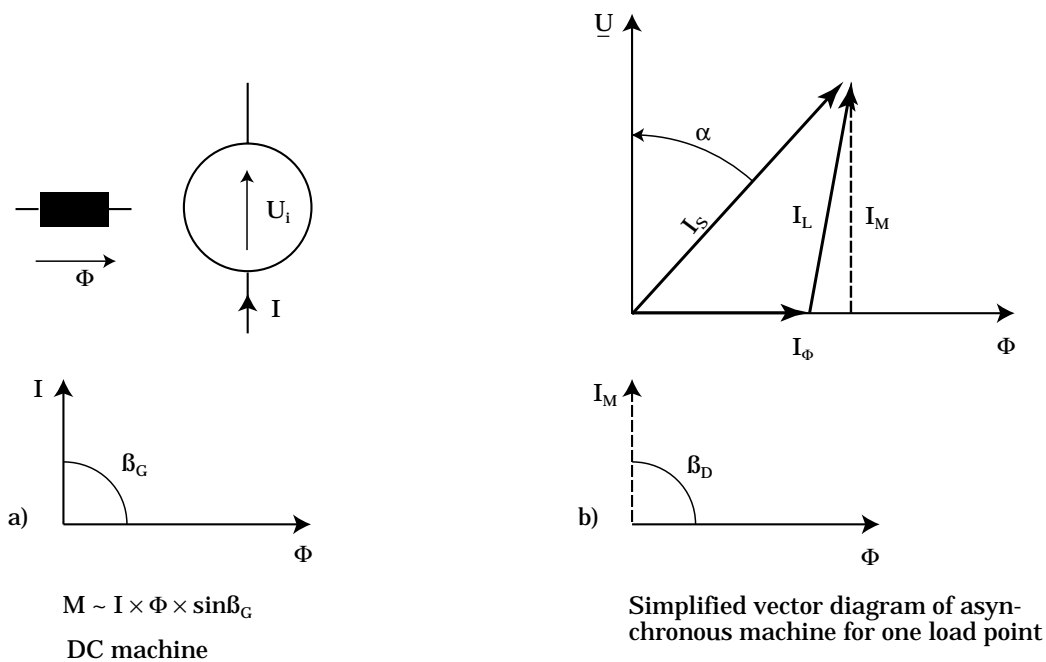
Fig. 2.35   Comparison between DC and AC asynchronous machines

Using a mathematical motor model, the torque can, however, be calculated from the relationship between the flux and the stator current.

The measured stator current (I_S) is separated into the component that generates the torque (I_L) with the flux (Φ)at right angles to these two variables (I_B). These generate the motor flux (Fig. 2.36).

$$T \sim I_S \times \Phi_L \times \sin\theta$$

ω: Angular velocity

I_S: Stator current

I_B: Flux-generating current

I_W: Active current/rotor current

Φ_L: Rotor flux
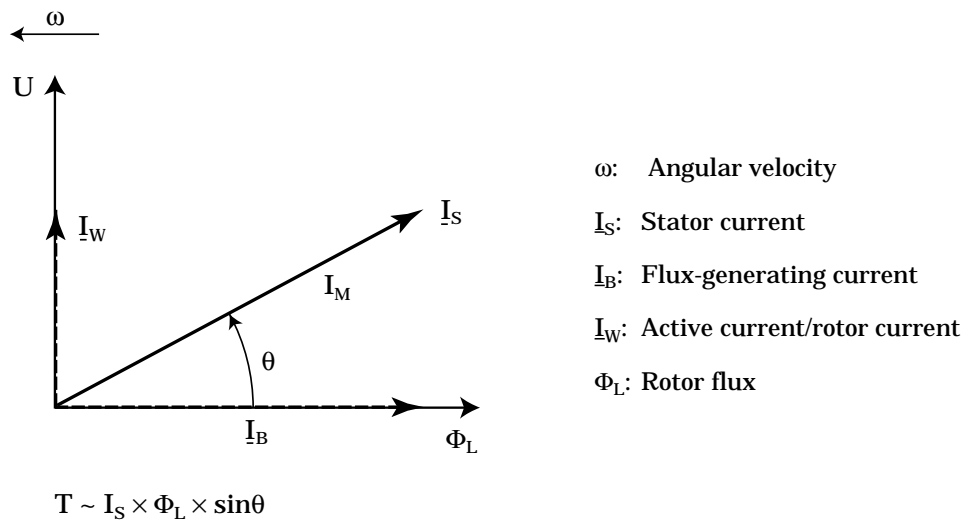
Fig. 2.36   Calculation of the current components for field-oriented regulation

Using the two current components, torque and flux can be influenced independently. However, as the calculations, which use a dynamic motor model, are quite complicated, they are only financially viable in digital drives.

As this technique divides the control of the load-independent state of excitation and the torque it is possible to control an asynchronous motor just as dynamically as a DC motor – provided you have a feedback signal. This method of three-phase AC control also offers the following advantages:

• good reaction to load changes
• precise speed regulation
• full torque at zero speed
• performance comparable to DC drives.

V/f characteristic and flux vector control

The speed control of three-phase AC motors has developed in recent years on the basis of two different control principles:

normal V/f or SCALAR control, and
flux vector control.

Both methods have advantages, depending on the specific requirements for drive performance (dynamics) and accuracy.

V/f characteristic control has a limited speed regulation range of approximately 1:20 and at low speed, an alternative control strategy (compensation) is required. Using this technique it is relatively simple to adapt the frequency converter to the motor and the technique is robust against instantaneous loads throughout the speed range.

In flux vector drives, the frequency converter must be configured precisely to the motor, which requires detailed knowledge. Additional components are also required for the feedback signal.

Some advantages of this type of control are:
• fast reaction to speed changes and a wide speed range
• better dynamic reaction to changes of direction
• it provides a single control strategy for the whole speed range.

For the user, the optimum solution lies in techniques which combine the best properties of both strategies. Characteristics such as robustness against stepwise loading/unloading across the whole speed range - a typical strongpoint of V/f-control - as well as fast reaction to changes in the reference speed (as in field-oriented control) are clearly both necessary.

Danfoss VVC^{plus} is a control strategy that combines the robust properties of V/f control with the higher dynamic performance of the field-oriented control principles and has set new standards for drives with speed control.

VVC^{plus} Slip compensation

Independently of the actual load torque, the magnetic field strength of the motor and the shaft speed are maintained at the speed reference command value. This is done using of two equalising functions: slip compensation and the load compensator.

The slip compensation adds a calculated slip frequency (Δf) to the rated speed signal in order to maintain the required reference frequency (Fig. 2.31). The rise in stator frequency is limited by a user-defined run-up time (ramp). The estimated slip value is taken from the estimated value of the torque load and the actual magnetic field strength – so the magnetic field weakening is also taken into consideration.

The stationary behaviour of the control system is illustrated together with the torque/speed graphs in Fig. 2.37.
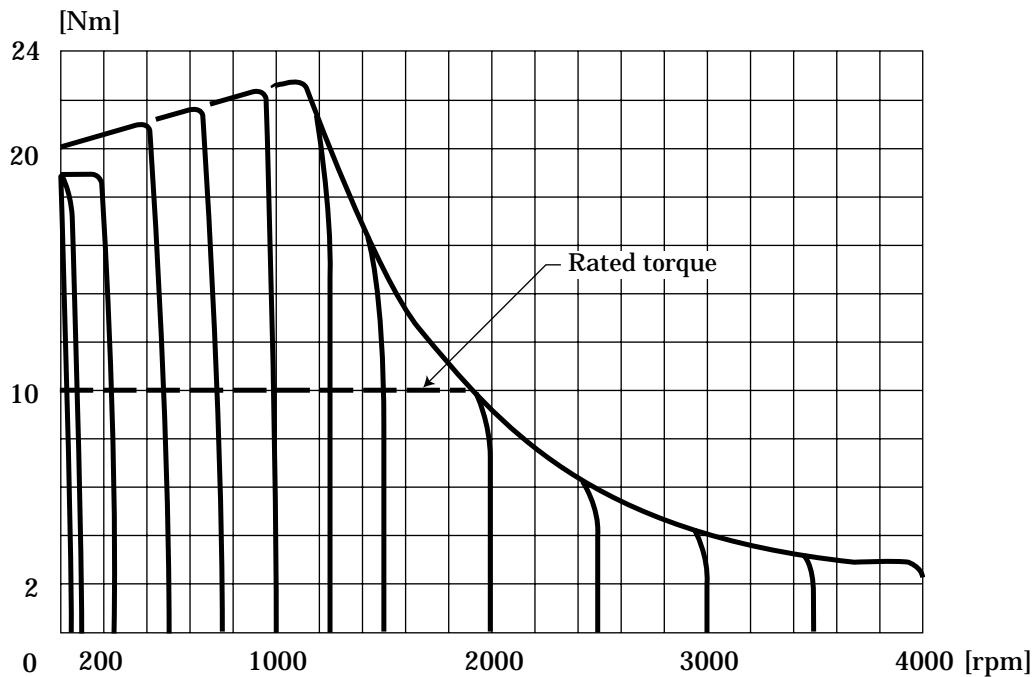
Fig. 2.37   Torque/speed characteristics (Rated torque 10 Nm)

Automatic Motor Adaptation (AMA)

Automatic tuning functions simplify installation and commissioning, by optimising the drive to the motor.

In order to ensure installation-related deviations of the electrical parameters are taken into account the stator resistance and inductance are measured. Then, during operation, the motor connections must be checked for correctness to ensure the data validity.

Briefly, the new no-spin AMA removes the need for time consuming manual motor compensation and makes the drives remarkably user-friendly and easy to commission. In addition, as the parameters are automatically correctly tuned, optimum motor efficiency is achieved – guaranteeing improved performance – and thus financial savings.

The latest methods of AMA measure the actual values of stator resistance and stator inductance for use in the static motor model, resulting in a significantly more accurate tuning to the motor. Importantly, the motor parameters are measured without turning the motor shaft – so the drive does not have to be decoupled from the motor. This feature has real customer benefits as, during the commissioning of a new plant, the mechanical work is usually done first; having to subsequently de-couple the drive during the electrical commissioning phase is an expensive and unpopular option.

Automatic Energy Optimization (AEO)

Energy saving is vital in industry today. In many applications where drives run in different load cycles energy can be saved during operation with low loads by reducing the magnetic field strength.

In many drives, particularly ones used on quadratic loads (such as fans and rotary pumps) special V/F characteristics can also be set to increase the energy savings.

There is a procedure which automatically optimises the energy consumption at the given actual load and adapts the speed reference which supplies the magnetic field strength for the actual load. As a compromise between the optimum savings and the real-life application requirements for minimum torque for locked rotors (or stalling torque) a lower limit has been set.

The settings are based solely on the data available in the control system; for these functions there is thus no need for extra adjustment of parameters. Contrary to the normal speed-controlled operation with magnetic rated field strength, energy optimisation prevents losses in the motor and thus saves energy. The average energy saving potential for small-to-medium-sized drives is 3 to 5% of the rated power during operation under small loads. As a very important side-effect and additional benefit, the motor runs almost without a noise under small loads – even at low to medium switching frequencies.

Operation at the current limit

Voltage-sourced PWM frequency converters which work in accordance with simple V/f characteristic control are not normally able to work "smoothly" at current limit. The voltage (and, therefore, the frequency) is first reduced until the preset current limit has been obtained. As soon as this limit has been reached, the frequency converter tries to reach the preset speed reference again (voltage and frequency are again increased). This leads to an increase or reduction of the speed, which places an unnecessary burden, in particular, on the mechanics of the system and may have a negative impact on the quality of the product.

In some situations, a sudden trip may occur:
• when an internal ramp is used to reduce or increase the voltage and frequency, or
• if the load is reduced.

Today's PWM frequency converters use an internal ramp to search for a working point at which the preset current limit is not exceeded and then control the motor smoothly to this working point. A warning signal is fed back to notify the user that the current limit has been reached. The frequency converter will not trip, unless no suitable frequency can be found.

Protective functions

VVC^{plus} provides a protection scheme that helps build a robust, intelligent power circuit, while at the same time keeping the costs of frequency converter and motor protection as low as possible. This is achieved by using a digital protection strategy, based on re-using the signals required by the control system and the use of fast, digital signal processing (ASIC) instead of passive power components (such as AC coils).

The inverter is protected against all faults except branch shoot-through when appropriate dead time control and a properly designed gate drive can be used. Each IGBT is galvanically separated from the supply voltage and the control signal by means of gate drive transformers.

Current and temperature are transmitted to the ASIC either through an analogue/digital converter or a comparator. The "fault monitoring" function in the ASIC processes the signals as required to perform the appropriate protective function (current, steps 1 and 2 (Fig. 2.38). In order to limit the size of the ASIC, fault monitoring is carried out at a second level in the micro-processor (current, steps 3 and 4 (Fig. 2.38).

Overcurrent protection:
Fig. 2.38 shows how different "filter times" (time before the frequency converter trips) result from different currents. Trigger level and "filter time" can be adjusted to ensure the maximum noise immunity for the individual inverter switch (overcurrent ruggedness of the IGBT). Noise in this sense is both real noise (interference) and short overloads, such as the switching on the inverter on long motor cables. To make the inverter even more robust, a second "filter time" has been added.
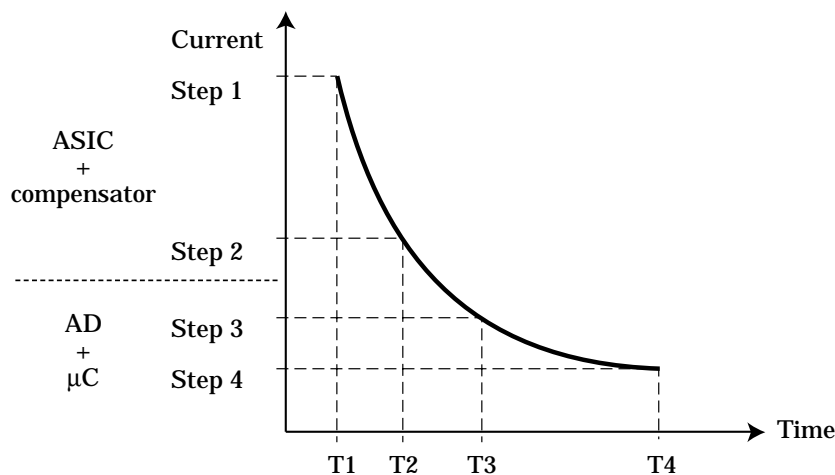

Fig. 2.38   Overcurrent steps

This "filter time" determines at which frequency and how often the inverter successfully turns on before finally being locked (current level 1). The user sets the filter time T4 and the current level 4.

Example:
For machine-specific reasons, a 4-pole 1.5 kW motor is only allowed to draw 4 A for 5 secs. This means that T4 = 5 secs. And current level 4 = 4 A.

The rest is determined by the controls and the hardware current limit of the frequency converter.

Such an overcurrent protection scheme, which takes advantage of the ruggedness of the new generation IGBTs, provides a highly robust inverter without having to use extra passive components, such as motor coils.

High temperatures protection:
The temperature of the heat sink (T_C) (Fig. 2.34) is measured directly and the inverter losses ($P_{loss,WR}$) are calculated on the assumption that the temperature of the heat sink is determined by the ambient temperature, the cooling conditions and the inverter losses, and that the inverter IGBTs are the limiting components.

By combining the measured values for T_C and $P_{loss,WR}$, it is possible to set the drive optimally to the actual working conditions. Normally, this is a question of changing the switching frequency and the output current in relation to the cooling conditions, the mains voltage and the ambient temperature.
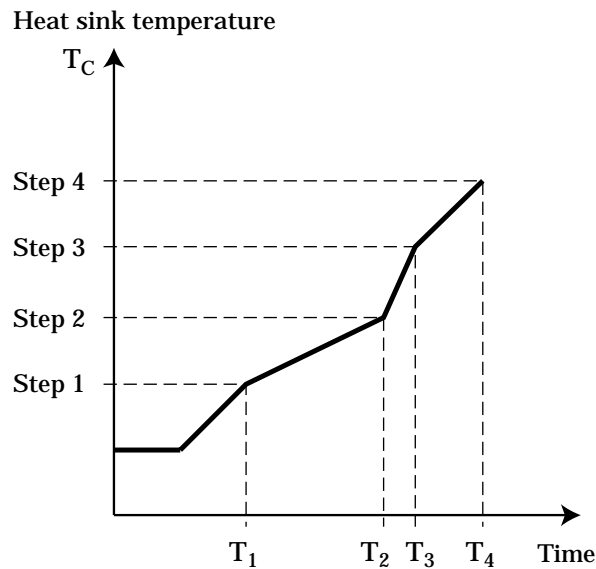
Fig. 2.39   Overtemperature levels

Fig. 2.39 gives an example in which the temperature signal is used to give the user time to react to a fault by correctly connecting a frequency converter fan.

At time T_1 the switching frequency of the inverter is reduced; the noise level (interference) increases and a warning signal is given as a feedback indication. At T_2 the output voltage is reduced, maximum torque is limited and an additional signal is given. At T_3 a predefined minimum current is reached and a third warning is given. The user now has the choice of a controlled motor stop or of letting it run with the risk that at T_4 the inverter will finally trip.

This intelligent fault monitoring protection scheme enables efficient use of the inverter chip and guarantees a sturdy and highly "fault-tolerant" drive. In addition, the user can pre-program the frequency converters reaction to a given fault situation.

The microchip in general

The microchip consists of three basic units, each with a special task.
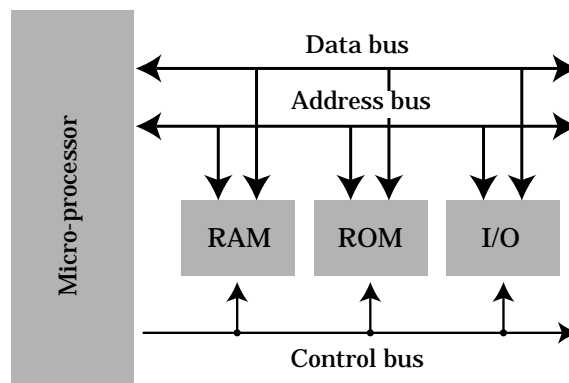
Fig. 2.40   Principle diagram of the computer

The micro-processor controls the chip and, if it receives the right sequence of instructions (programs), it is able to carry out a number of functions in the computer memory as well as controlling all the other units in the chip.

The computer memory often takes the form of an EPROM (**E**rasable **P**rogrammable **R**ead **O**nly **M**emory). EPROMs retain their contents if the voltage to the circuit is switched off and information in an EPROM can be programmed and deleted by means of ultra violet rays, making it possible to use it again and again. Unlike EPROMs, PROMs, which are not erasable, can only programmed once.

RAM (**R**andom **A**ccess **M**emory) is the memory from which the micro-processor collects and stores data. RAM loses its information if the voltage is switched off and the contents are then undefined when the voltage comes back.

The third unit is marked I/O, and contains the inputs and outputs required by the computer for its communication purposes. These could be connections to control panels, printers or other electronic equipment.

The bus is a collection of wires that connects the individual units to the microprocessor. The data bus transmits data between units, the address bus signals where the data is to be sent and the control bus monitors the transmission to see that its sequence is right.

Computers for frequency converters

In addition to the RAM, ROM and I/O frequency converters, chips contain a number of additional units including an EEP-ROM (Electrically Erasable PROM) which enables the user to program the computer. EEPROM's can be programmed or reprogrammed using electrical signals something that is necessary when programming the frequency converter (design data) and for storing special tasks.

In addition, a frequency converter chip can be equipped with an ASIC. This is an integrated switching circuit in which some functions are determined by semi-conductor manufacturers and the remaining functions can be programmed to match specific tasks set by the frequency converter manufacturer such as the control principle.

Control card inputs – and outputs

The plant in which the frequency converter will be used determines the need for in- and outputs.

Frequency converters in automated plants must receive both analogue and digital control signals. Analogue signals can assume all values within a certain range. Digital values can assume two values (0 or 1).
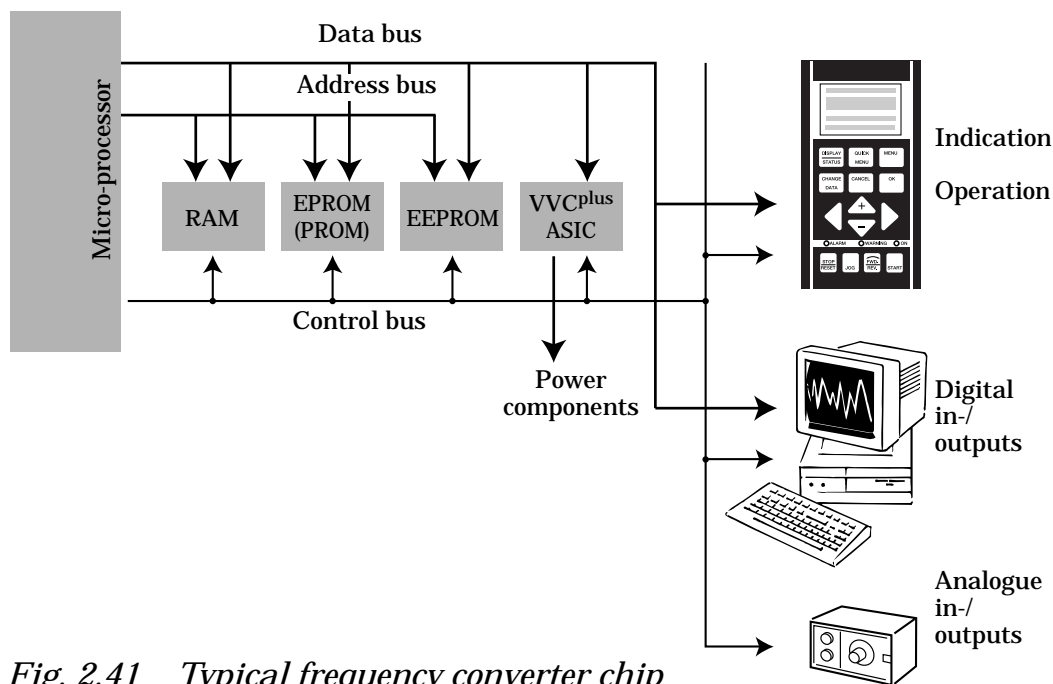
Fig. 2.41   Typical frequency converter chip

Fig. 2.42   Analogue signal (a) and digital signal (b)

There is no standard for control signals. However, some signals have become de facto standards – such as 0-10 V or 0/4-20 mA for analogue signals. Since semi-conductors are used in the digital signal, the digital output must receive a minimum current to make the signal "reliable". A typical signal range is 20-30 V and 10-500 mA.

The digital outputs of a PLC (**P**rogrammable **L**ogic **C**ontroller) are matched to the digital inputs of the frequency converter. As a minimum, these accept voltages typically between 10 and 30 V and draw a current of at least 10 mA at 20 V. The internal resistance of the signal inputs can thus be a maximum of 2 kOhm.

Communication

Basically, digital frequency converters are able to exchange data with the peripherals using three interfaces (Fig. 2.43).

- the conventional control terminal for digital and analogue in- and outputs,
- the control panel with displays and keyboard,
- a serial interface for service, diagnosis and control functions.

Depending on the application, the communication can be supplemented by an intelligent serial interface for a high-performance bus (such as PROFIBUS). This may be in the form of an independent group of units which may contain their own supporting micro-processor and peripherals (e.g. Dual Port Ram).

Fig. 2.43   Basic concept – communication (frequency converter)
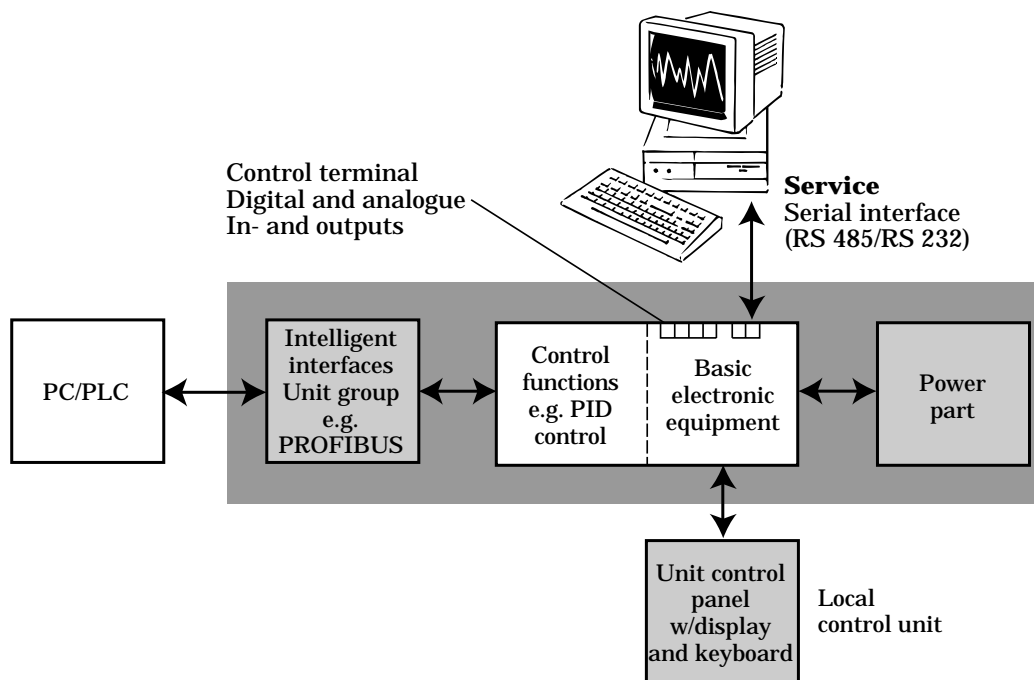
A control panel with display and keyboard can be integrated into almost every digital frequency converter. In the control terminal the minimum of data cables is always the number of connections, plus 1, which means that the number of cables depends on the tasks and the number of terminals. The individual terminals can of course be programmed for different tasks.

The display makes it possible to monitor the frequency converter which can be helpful when diagnosing faults such as wire breakage and missing control signal.
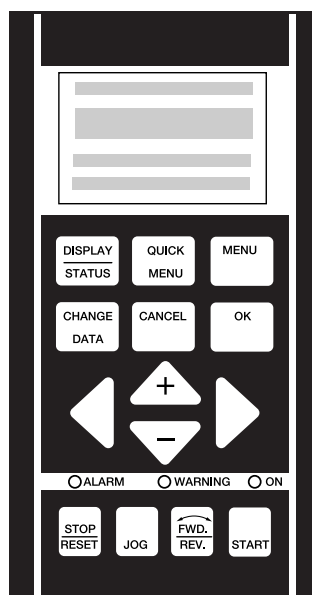
Fig. 2.44   Frequency converter local control unit

In a process, the frequency converter is regarded as being an active component and can either be with, or without, feedback ie: closed loop (regulation) or open loop control.

An open loop control system can be operated using a simple potentiometer but closed loop controls are usually more complex, needing feedback and setpoint control.

PLC's

Programmable Logic Controllers (PLC's) are able to supply both control signals (speed) and commands (start, stop, reversing).

One of the major benefits of PLC's is that they are able to read, and continuously collect, the output signals – such as motor current and motor frequency – generated by a frequency converter. This is a significant improvement over using a simple indicating instrument.

A PLC system consists of three basic elements:
• central unit,
• in- and output modules,
• programming unit.
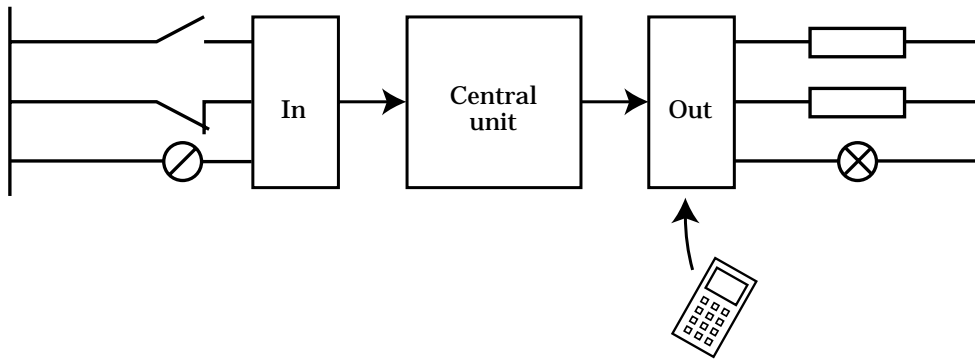
Fig. 2.45   Principal structure of a PLC

The programming unit develops a control program for the control unit and this program is actioned by the central unit which sorts the input signals and activates the output signals. The central unit is only able to work with digital signals which alternate between two values, (24 V and 0 V) – the high voltage being "1" or "ON", and the lower voltage "0" or "OFF".

Fig. 2.46   The digital signal can be "ON" or "OFF" for shorter or long intervals of time

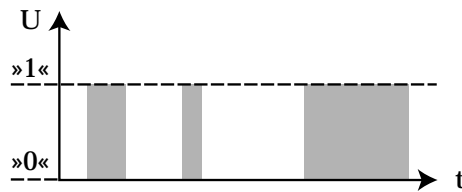Usually a frequency converter and a PLC are connected in one of two different ways – either directly or using serial communication. When directly connected the in- and outputs of the PLC are connected to the in- and outputs of the frequency converter one by one by using individual cables. The in- and outputs of the PLC thus replace separate components, such as potentiometer, control contacts and indicating instruments.

Serial Communication

With serial communication, signals are transmitted via pairs of wires. In the period t_1 -t_2 , information A is transmitted; in the period t_2 -t_3, information B is transmitted, etc. This type of information transmission is called serial communication (Fig. 2.47).

D/D = transducer digital/digital
D/A = transducer digital/analogue
A/D = transducer analogue/digital
S   = transmit serial data
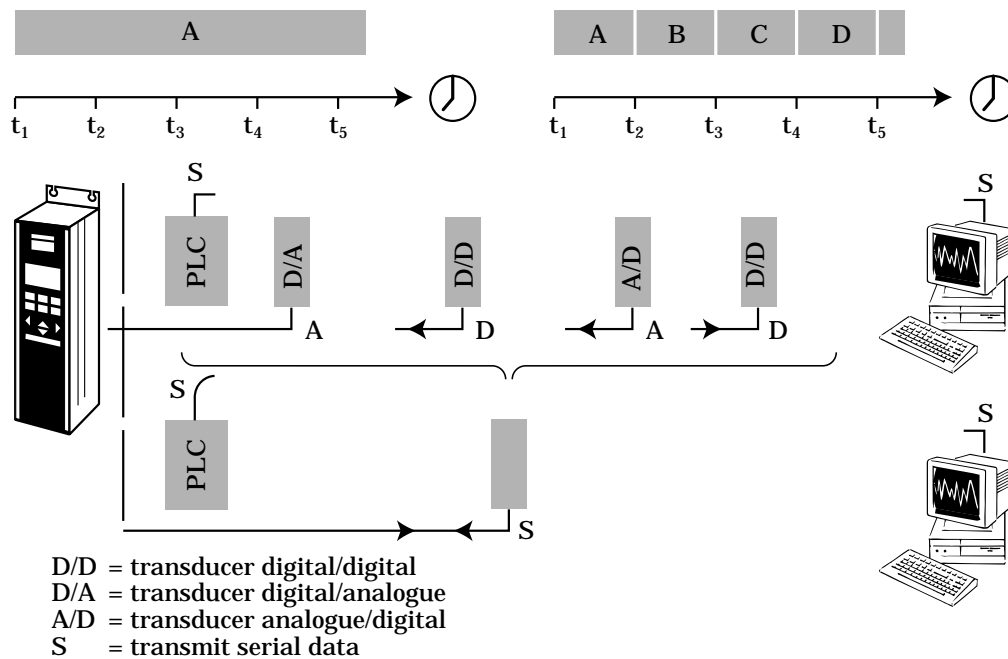
Fig. 2.47   Serial communication guarantees a fast signal transmission and a simplified installation
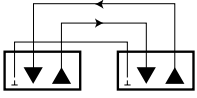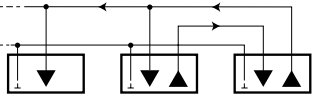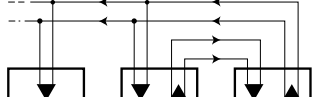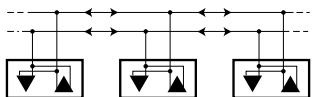
There are three main principles for serial communication but the decisive factors are the number of units that have to communicate with each other and the speed of operation.

You can either use a large number of wires to transmit and receive information to and from every unit on the system, or you can use two wires. In the two wire systems either several receivers can be connected to one transmitter (S) or all the connected units can transmit and receive. This last arrangement is called a bus.

On the bus all the units must have the same signal level to ensure that they can communicate and are able to receive the serial signal.

In addition, the units must have the same signal structure (protocol) to ensure that the receiver understands the information sent. Structure and combination of signals are subject to a number of standards.

The common signal level is not subject to any particular value. Consequently, the software in the units must be matched so that the common signal level can be determined.

Principle	Standard (application)	No. of units/ sets of wires	Max. distance m	No. of wires	Signal level
	RS 232 (Point to Point)	1 trans- mitter 1 receiver	15	Duplex: min. 3 + div. Status signals	±5 V min. ±15 V max.
	RS 423 (Point to Point)	1 trans- mitter 10 receivers	1200	Duplex: min. 3 + div. Status signals	±3,6 V min. ±6 V max.
	RS 422 (Point to Point)	1 trans- mitter 10 receivers	1200	Duplex: 4	±2 V min.
	RS 485 (Bus)	32 trans- mitters- 32 receivers	1200	Semi duplex: 2	±1,5 V min.

▲ : Transmitter
▼ : Receiver

Fig. 2.48   Standards for serial connections

RS 232 is the most widely known standard. Its use is limited to short transmission distances and low transmission speeds.
RS 232 is thus used where signals are only transmitted occasionally. This could be, for example, in connection with terminals and printers.

RS 422 and 423 solve the problem of distance and transmission speed of RS 232 and are therefore often used in process automation, with a PLC, where the signal transmission is more continuous.

RS 485 is the only standard that enables connection and operation of a higher number of units as well as communication between a number of units via a common pair of wires.

This type of connection only requires two wires to enable the units to take turns at sending and receiving data using a bus.

There are three types of signal for communicating between a PLC/PC and a frequency converter:
- control signals (speed, start/stop/reversing)
- status signals (motor current, motor frequency, frequency reached)
- alarm signals (motor stopped, overtemperature)
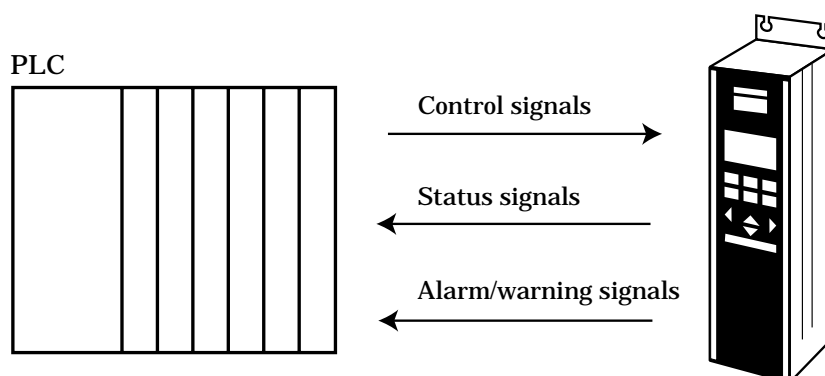
Fig. 2.49   Three types of signal between a PLC and a frequency converter

The frequency converter receives control signals from the PLC and then controls the motor. It also sends status signals to the PLC and provides information about the effects of the control signals on the motor/process. If the frequency converter stops because of abnormal operating conditions, alarm signals are transmitted to the PLC.

RS 485 enables the connection of different structures of process control systems. For example it enables a PLC to be installed in a control panel from where it can control a number of frequency converters or other remote field devices in other control panels.
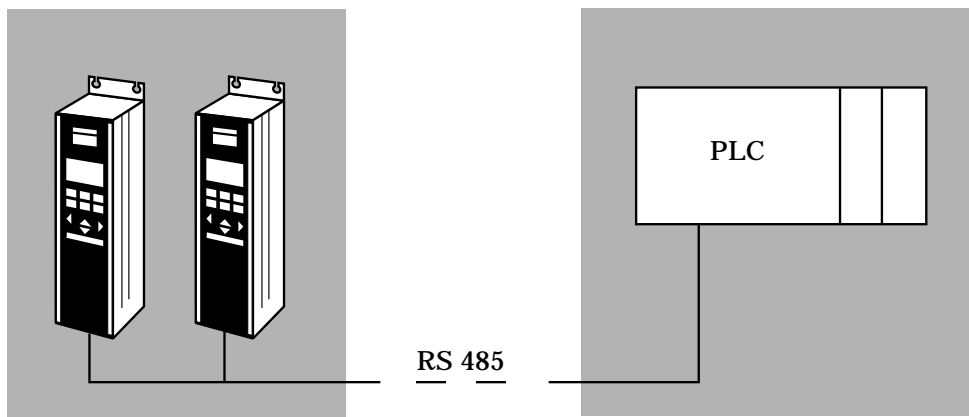
Fig. 2.50   The bus enables many different build-ups

With the change from analogue to digital technology, serial interfaces become more and more widely used for frequency converters in connection with:
• equipment testing
• commissioning
• service
• automated operation
• visualisation and monitoring
• flexibility.

To exchange information between the frequency converter and PLC or PC over a serial interface, a protocol is required. The protocol determines both the maximum length of the information (telegram) and where individual items of data are placed in the information chain.

Furthermore, the protocol offers the following general functions:
• selection (address) of the component used
• data requirements of the component (e.g. rated current/voltage values)
• data transfer to the individual components (e.g. rated values, limit values of current/frequencies) through their addresses, and
• data transfer to all units (BROADCAST), which enables functions such as simultaneous stop/start where feedback from the units is not required.

Most of industrial equipment vendors use their own protocol, which can be problem for the user who then needs to write a driver for his PC or PLC so it can communicate. Also the user cannot put equipment from different vendors on the same serial link as they will not share a common data structure, and may operate at different speeds.

Manufacturer-independent communication

However major manufacturers have collaborated to develop 'open' universal fieldbus systems over which all industrial equipment can communicate regardless of its manufacturer. One of the most well supported and well proven fieldbus networks for all products, including drives, is PROFIBUS.

Other buses include:
• Modbus +
• Interbus-S
• Device Net
• Lonworks.

Profibus has three different implementations, developed for different applications:

FMS (Fieldbus Message Service) Protocol
This is the universal solution for communication assignments. Because of its high flexibility, FMS services are able to solve extensive communication assignments at medium data speed. The FMS protocol is used in areas such as the textile industry, building management and drive technology, actuator and sensor technologies as well as low-voltage switching components.

DP (Decentral Peripherals) Protocol

DP, which has been optimised with respect to speed, is largely used for communication between automation systems and decentral peripheral units. It is suitable as a replacement for cost-intensive parallel signal transmission via 24 V and the transmission of measured values via 20 mA and is mainly used in high speed automated manufacturing plants.

PA (Process Automation)

PROFIBUS-PA is a PROFIBUS variant for use in process automation. PROFIBUS-PA uses the intrinsically safe transmission technique laid down in IEC 1158-2 and enables remote feeding of participating units via the bus.

1. Three-phase AC motors

The first electric motor, a DC unit, was built in 1833. The speed regulation of this motor is simple and fulfils the requirements of the many different applications and systems.

In 1889, the first AC motor was designed. More simple and robust than the DC motor, the three-phase AC unit suffered from fixed speed values and torque characteristics, which is why, for many years, AC motors could not be used in special-duty applications.

Three-phase AC motors are electromagnetic energy converters, converting electrical energy into mechanical energy (motor operation) and vice versa (generating operation) by means of electromagnetic induction.

The principle of electromagnetic induction is that if a wire is moved through a magnetic field (B), a voltage is induced. If the wire is in a closed circuit, a current (I) will flow. When the wire is moved, a force (F), which is vertical to the magnetic field, will act on the wire.

a) Generating principle (induction by means of movement).
In the generating principle, moving a wire in the magnetic fields generates a voltage (Fig. 1.01a).

b) Motor principle
In motors, the induction principle is reversed and a current-conducting wire is positioned in a magnetic field.
The wire is then influenced by a force (F) that moves the wire out of the magnetic field.

a) Generator principle   b) Motor principle
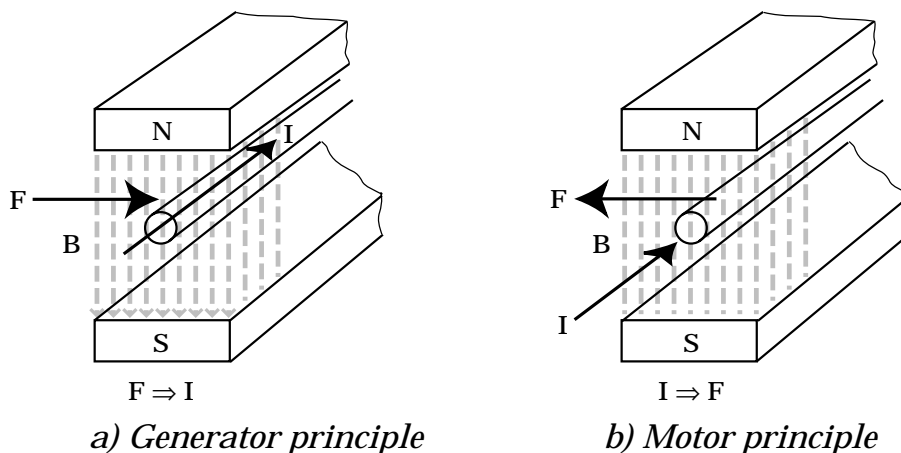
Fig. 1.01   Principle for electromagnetic induction

In the motor principle, the magnetic field and current-distributed wire generate the movement (Fig. 1.01b).

The magnetic field in the motor is generated in the stationary part (the stator) and the wires, which are influenced by the electromagnetic forces, are in the rotating part (the rotor).

Three-phase AC motors can be divided into two main groups: asynchronous and synchronous motors.

The stators basically work in the same way in both types, but the design and rotor movement in relation to the magnetic field differs. In synchronous (which means simultaneous or the same) the speed of rotor and magnetic field are the same and in asynchronous the speeds are different.
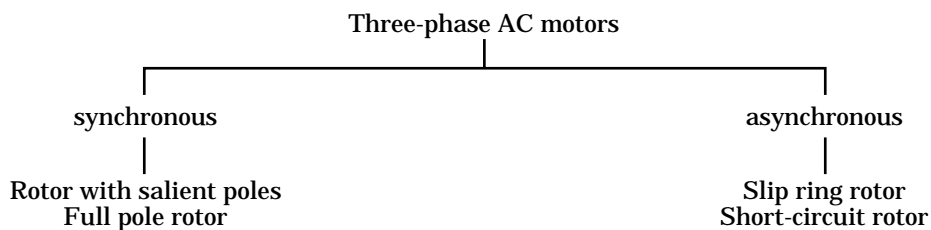
Fig. 1.02   Types of three-phase AC motors

Asynchronous motors

Asynchronous motors are the most widely used and require practically no maintenance. In mechanical terms, they are virtually standard units, so suitable suppliers are always nearby. There are several types of asynchronous motors, all of which work on the same basic principle.
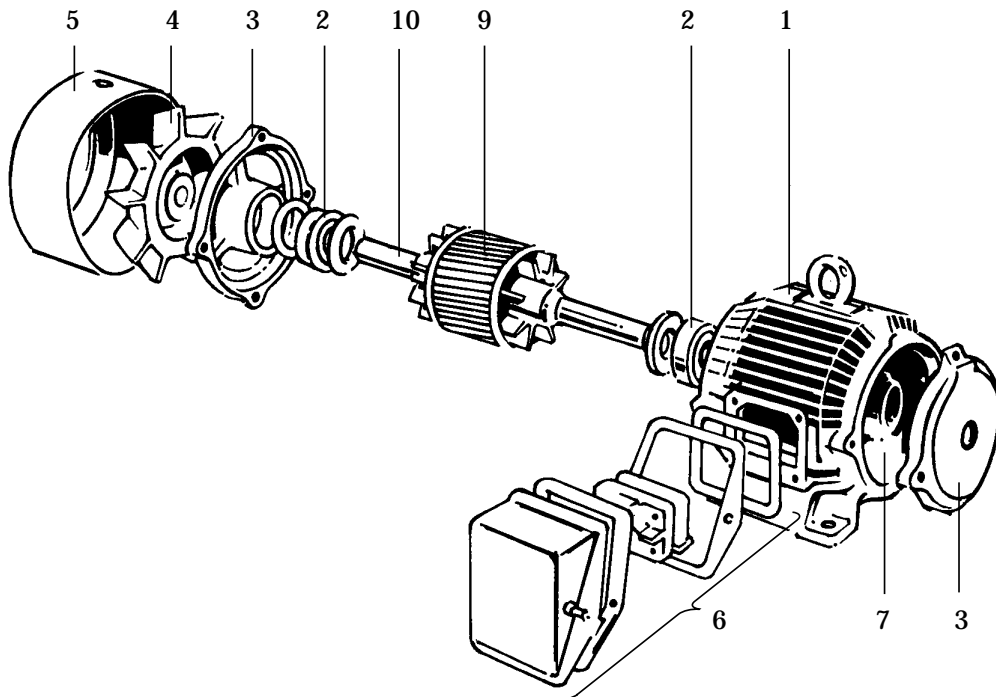
The two main components of an asynchronous motor are the stator (stationary element) and the rotor (rotating element).

Stator

Fig. 1.03   Build-up of an asynchronous motor

The stator is a fixed part of the stationary motor. It consists of a stator housing (1), ball-bearings (2) that support the rotor (9), bearing blocks (3) for positioning of the bearings and as a finish for the stator housing, fan (4) for motor cooling and valve casing (5) as protection against the rotating fan. A box for electrical connections (6) is located on the side of the stator housing.

In the stator housing is an iron core (7) made from thin (0.3 to 0.5 mm) iron sheets. These iron sheets have punched-out sections for the three phase windings.

The phase windings and the stator core generate the magnetic field. The number of pairs of poles (or poles) determines the speed at which the magnetic field rotates. If a motor is connected to its rated frequency, the speed of the magnetic field is called the synchronous speed of the motor (n_0).

Pole pairs (p)	1	2	3	4	6
Number of poles	2	4	6	8	12
n_0 [1/min]	3000	1500	1000	750	500

Table 1.01   Pole pairs (p), pole number and synchronous motor speed

Magnetic field

The magnetic field rotates in the air gap between stator and rotor. After connecting a phase winding to a phase of the supply voltage, a magnetic field is induced.
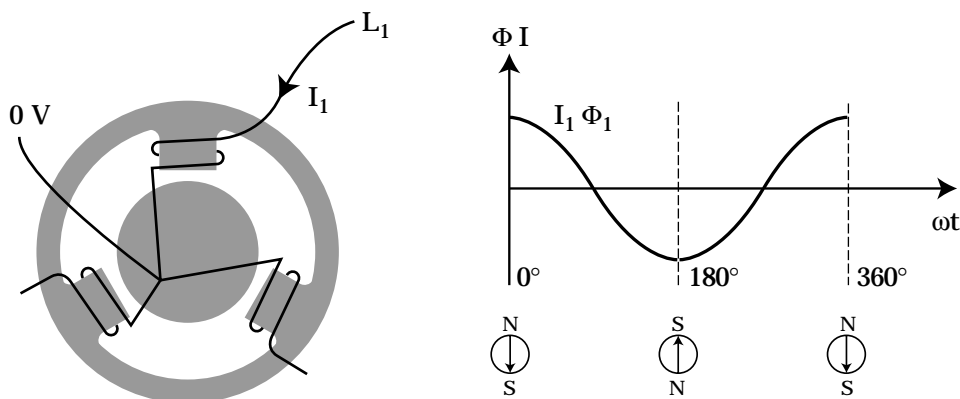
Fig 1.04   One phase results in an alternating field

The position of this magnetic field in the stator core is fixed, but its direction changes. The speed at which the direction changes is determined by the frequency of the supply voltage. At a frequency of 50 Hz the alternating field changes direction 50 times per second.

If two phase windings are connected to each phase at the same time, two magnetic fields are induced in the stator core. In a two-pole motor, there is a 120 degree displacement between the two fields. The maximum values of the fields are also displaced in time.

This results in the creation of a magnetic field that rotates in the stator. However, the field is highly asymmetrical until the third phase is connected.
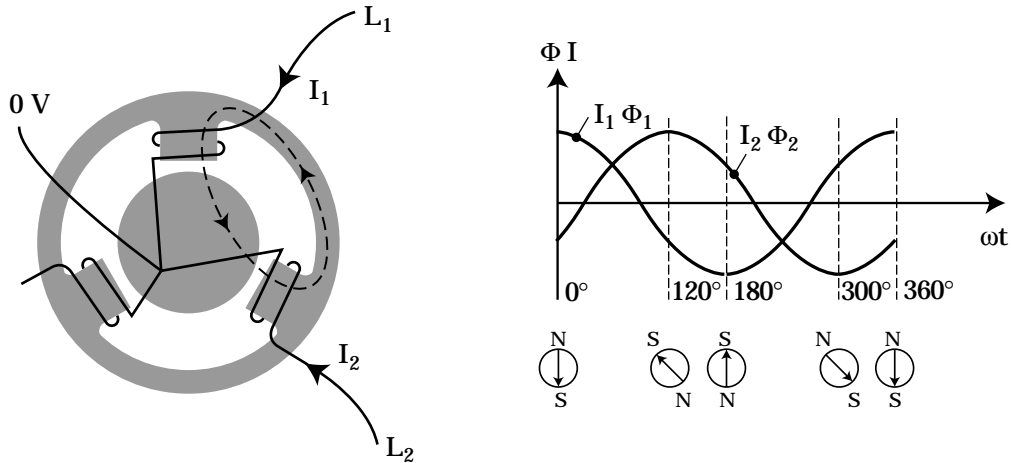
Fig. 1.05   Two phases result in an asymmetrical rotating field

The three phases generate three magnetic fields in the stator core which are displaced 120 degrees in relation to each other.
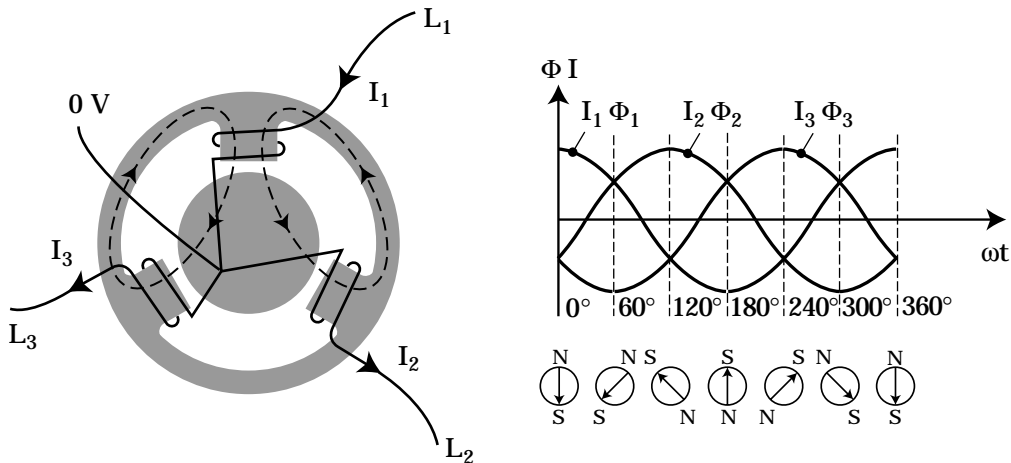
Fig. 1.06   Three phases result in a symmetrical rotating field

The stator is now connected to the three-phase supply voltage and the magnetic fields of the individual phase windings build a symmetrical, rotating magnetic field called the motor rotating field. The amplitude of the rotating field is constant at 1.5 times the maximum value of the alternating fields. Rotation is at:

$$n_0 = \frac{(f \times 60)}{p} \ [1/\text{min}]$$

f =   frequency
n_0 =   synchronous speed
p =   no. of pole pairs

The speed therefore depends on the number of pairs of poles (p) and the frequency (f) of the supply voltage. The illustration below shows the size of the magnetic fields (F) in three different periods.
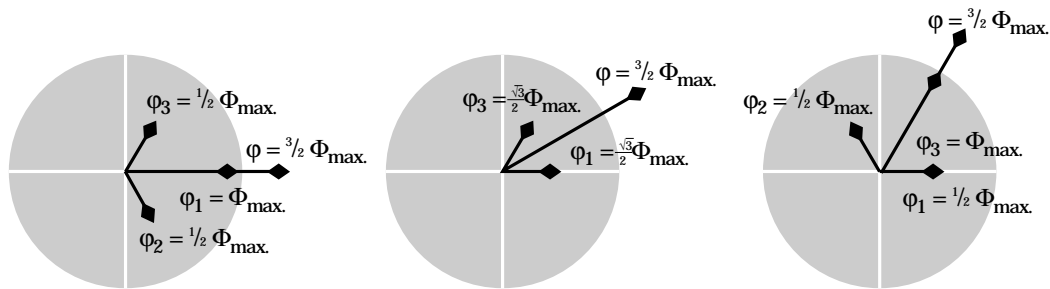
Fig. 1.07   The size of the magnetic fields is constant

The visualisation of the rotating field with a vector and a corresponding angular velocity makes up a circle. As a function of time in a system of co-ordinates, the rotating field makes up a sinusoidal curve. The rotating field becomes elliptic if the amplitude changes during a rotation.

Rotor

The rotor (9) is mounted on the motor shaft (10) (see Fig. 1.03).

Like the stator, the rotor is made of thin iron sheets with gaps punched through them. There are two main types of rotor: slip ring motors and short-circuit motors – the difference being determined by changing the windings in the gaps.

Slip ring rotors, like the stator, have wound coils placed in the gaps and there are coils for each phase coming to the slip rings. After a short-circuit of the slip rings, the rotor will function as a short-circuit rotor.

Short-circuit rotors have cast-in aluminium rods in the gaps. An aluminium ring is used at each end of the rotor to short-circuit the rods.

The short-circuit rotor is the more frequently used of the two. Since the two rotors principally work in the same way, only the short-circuit rotor will be described.
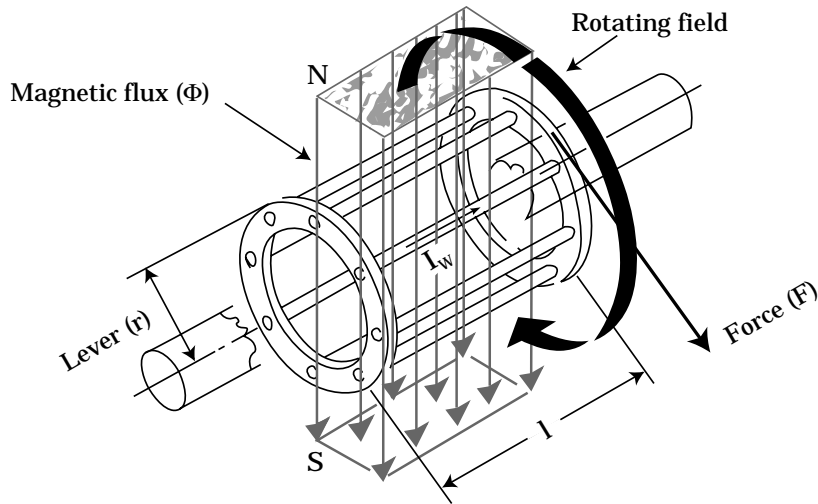
Fig. 1.08   Rotating field and short-circuit rotor

When a rotor bar is placed in the rotating field, a magnetic pole runs through the rod. The magnetic field of the pole induces a current (I_W) in the rotor bar which is only influenced by force (F) (Figs. 1.08 and 1.09a).

This force is determined by the flux density (B), the induced current (I_W), the length (l) of the rotor and the angle (q) between the force and the flux density

$$F = B \times I_W \times l \times \sin \theta$$

If θ is assumed to be = 90°, the force is

$$F = B \times I_W \times l \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots 1.01$$

The next pole that goes through the rotor bar has the opposite polarity. This induces a current in the opposite direction. Since the direction of the magnetic field has also changed, the force acts in the same direction as before (Fig. 1.09b).

When the full rotor is placed in the rotating field (see Fig. 1.09c), the rotor bars are affected by forces that turn the rotor. The speed (2) of the rotor does not reach that of the rotating field (1), since at the same speed no currents are induced in the rotor bars.
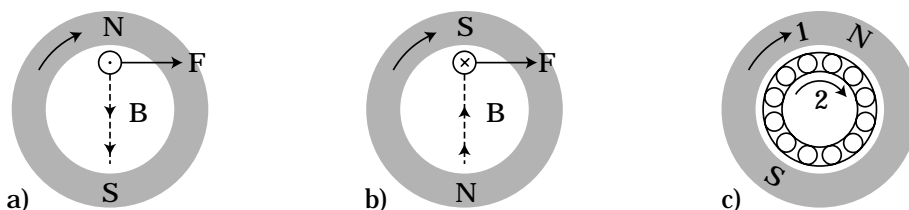

Fig. 1.09   Induction in the rotor bars

Slip, torque and speed

Under normal circumstances, the speed of the rotor, n_n, is lower than the speed of the rotating field, n_0. The slip, s, is the difference between the speed of the rotating field and the speed of the rotor:

$$n_0 = \frac{(f \times 60)}{p} \; [1/\text{min}] \qquad\qquad p = \text{no. of pole pairs}$$

The slip is often expressed as a percentage of the synchronous speed and is normally between 4 and 11 percent of rated speed:

$$s = n_0 - n_n$$

The flux density (B) is defined as the flux (Φ) per cross-sectional area (A). From equation 1.01 the following force can therefore be calculated:

$$s = \frac{n_0 - n_n}{n_0} \times 100[\%]$$

The force at which the current-conducting wire is moved is proportional to the magnetic flux (Φ) and the current (I_w) in the wire.

$$F = \frac{\Phi \times I_W \times l}{A} \; \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots 1.02$$

$$F \sim \Phi \times I_W$$

In the rotor bars, a voltage is induced via the magnetic field. This voltage allows a current (I_w) to flow through the short-circuited rotor bars. The individual forces in the rotor bars combine to set up a torque, T, on the motor shaft.
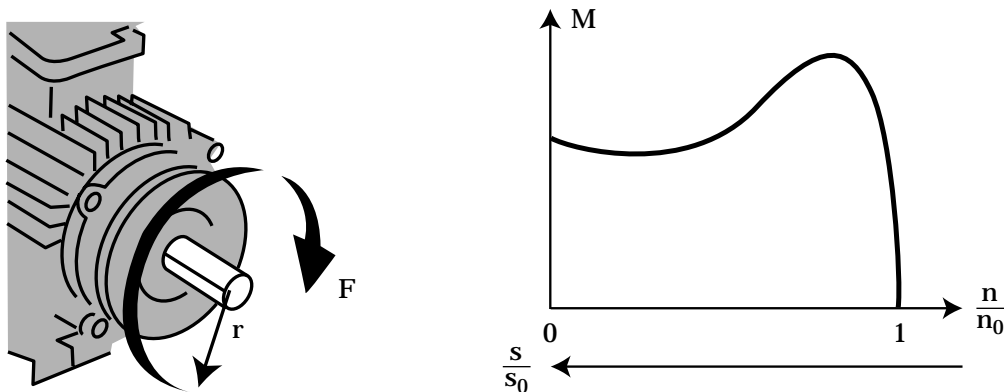

Fig. 1.10   The motor torque is "force multiplied by lever arm"

The relationship between motor torque and speed has a characteristic sequence which varies with the form of the rotor. The motor torque results in a force which turns the motor shaft.

The force arises, for example, in the circumference of a flywheel fitted to the shaft. With the force (F) and the radius (r) of the flywheel, the motor torque
$W = F \times r$ can be calculated.

The work done by the motor expressed as: $W \times F \times d$ where d is the distance that a motor pulls for a given load, n is the number of revolutions:
$d = n \times 2 \times p \times r$

Work can also be described as power multiplied by the time in which this power is active: $W = P \times t$.

The torque is thus:

$$T = F \times r = \frac{W}{d} \times r = \frac{(P \times t \times r)}{n \times 2\,\pi \times r}$$

$$T = \frac{P \times 9550}{n} \quad (t = 60 \text{ sec.})$$

This formula shows the relationship between the speed, n, the torque T [Nm] and the motor power P [kW].

The formula provides a quick overview when looking at n, T and P in relation to the corresponding values at a given operating point (n_r, T_r and P_r). The operating point is normally the rated operating point of the motor and the formula can be modified as follows:

$$T_r = \frac{P_r}{n_r} \quad \text{and for } P_r = T_r \times n_r,$$
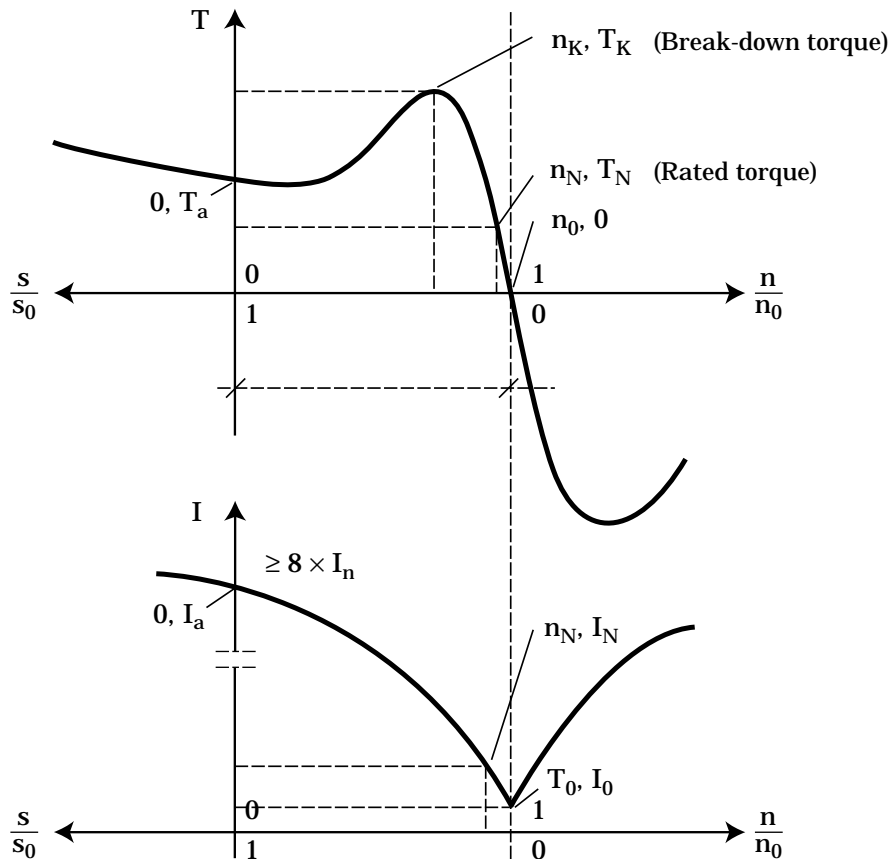
in which $T_r = \frac{T}{T_n}$, $P_r = \frac{P}{P_n}$ and $n_r = \frac{n}{n_n}$

In this proportional calculation, the constant – 9550 – is not applied.

Example:

Load = 15% of the rated value, speed = 50% of the rated value. The power generated is 7.5% of the rated power generated, since $P_r = 0.15 \times 0.50 = 0.075$.

In addition to the normal operating range of the motor, there are two brake ranges.

Fig. 1.11   Current and load characteristics of the motor

In the range where $\frac{n}{n_0} > 1$,   the motor is pulled above the synchronous speed and acts as a generator – creating an opposite torque, while at the same time giving an output back into the mains supply.

In the range of $\frac{n}{n_0} < 0$, braking is termed regenerative braking.

If two phases of a motor are suddenly swapped, the rotating field changes direction. Immediately after this, the speed ratio will be $\frac{n}{n_0} = 1$.

The motor, previously loaded with the torque T, now brakes with a braking torque. If the motor is not switched off at n = 0, it will continue running, but in the new direction of the rotating field.

The motor works in its normal range between $0 < \frac{n}{n_0} < 1$.

The motor's working range can be divided into two areas: start-up range $0 < \frac{n}{n_0} < \frac{n_k}{n_0}$ and operating range $\frac{n_k}{n_0} < \frac{n}{n_0} < 1$.

There are some important points in the working range of the motor:

T_a is the starting torque of the motor – the torque that builds up the motor power when rated voltage and rated frequency are being fed while at standstill.

T_k is the stalling torque of the motor. This is the largest torque the motor is able to generate while rated voltage and rated frequency are being fed.

T_n is the rated torque of the motor. The rated values of the motor are the mechanical and electrical values for which the motor was designed in accordance with the IEC 34 standard. These can be seen from the motor nameplate and are also referred to as name-plate values. The rated values indicate the motor's optimal operating point for direct connection to the mains supply.

Efficiency and losses

The motor takes up electrical power from the main supply. At a constant load, the input is larger than the mechanical output that the motor is able to provide due to losses – or inefficiencies – in the motor. The relation between output and input is the motor efficiency, η.

$$\eta = \frac{P_2}{P_1} = \frac{\text{Output power}}{\text{Input power}}$$

The typical efficiency of a motor is between 0.7 and 0.9, depending on the size of the motor and the number of poles.
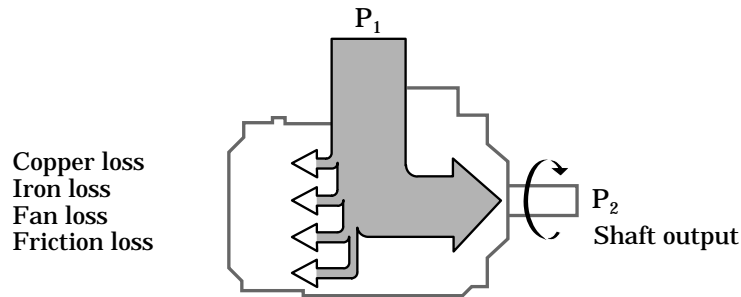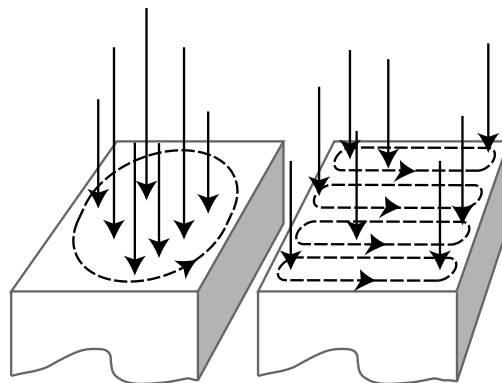
Fig. 1.12   Losses in the Motor

There are four main causes of losses in the motor – copper losses, iron losses, fan losses and friction losses:

Copper losses occur in the ohmic resistors of the stator and rotor windings.

Iron losses, consist of hysteresis losses and eddy current losses. Hysteresis losses occur when the iron is magnetised by an AC current and must be demagnetised at a 50 Hz supply voltage (v) 100 times per second. Both magnetising and demagnetising requires energy. The motor takes up input power in order to cover the hysteresis losses which increase with the frequency and the magnetic induction.

Eddy current losses occur because the magnetic fields induce electric voltage in the iron core and the wire. These voltages result in currents which lead to heat losses and move in circles around the magnetic fields.

By splitting up the iron core in thin sheets, the eddy current losses are drastically reduced.

Fig. 1.13   The eddy currents are reduced by laminating the iron in the motor.

Fan losses occur due to the air resistance of the motor fan.

Friction losses occur in the ball bearings of the rotor.

When determining the efficiency and motor output, the losses are calculated using a measured input.

Magnetic field

The motor has been designed for a fixed voltage and frequency and the magnetisation of the motor depends on the relationship between voltage and frequency.

If the voltage/frequency ratio increases, the motor is over-magnetised, if the ratio decreases, the motor is under-magnetised. The magnetic field of an under-magnetised motor is weakened and the torque which the motor is able to develop is reduced, possibly leading to a situation in which the motor does not start or remains at a standstill. Alternatively, the starting time may be extended, leading to a motor overload.

An over-magnetised motor is overloaded during operation. The power for this extra magnetisation is converted to heat in the motor and may damage the insulation. However, three-phase AC motors and – in particular – asynchronous motors are very robust so the problem of faulty magnetisation leading to load damage will only occur in continuous operation.

The way the motor runs indicates whether the magnetising conditions are poor – signs to watch for include declining speed at varying load, unstable or jerky operation of the motor, etc …

Equivalent circuit diagram

Principally, asynchronous motors consist of six coils: three coils in the stator and three coils in the short-circuit rotor (which magnetically behaves as if it consisted of three coils). By examining a set of coils it is possible to construct an electric diagram, which explains how the motor works.
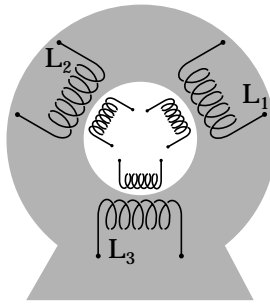
Fig. 1.14a   Layout of stators and rotors
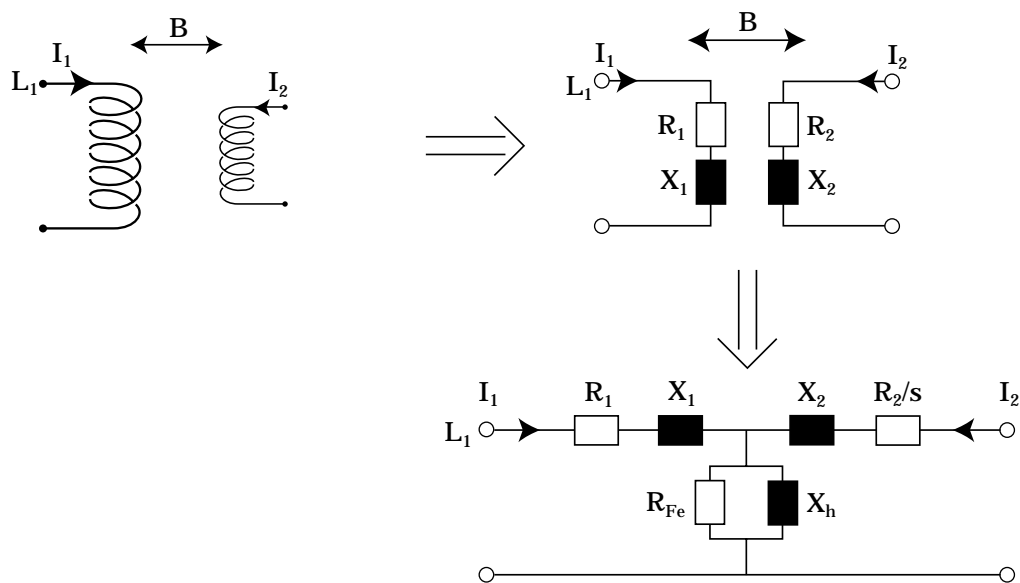
*Fig. 1.14b   Equivalent circuit diagram of the motor
(applies to phase L1)*

The stator coil current is not only limited by the ohmic resistance of the coil as each coil is connected to an AC voltage, an AC resistance builds up.
This resistance is termed reactance ($X_L = 2 \times p \times f \times L$) and measured in Ohms [$\Omega$].

f is the frequency and $2 \times \pi \times f$ is the angular frequency ω in $\frac{1}{s}$.

L is the inductance of the coil and is measured in Henry [H]. The effective current is limited by its dependence on the frequency.

The coils mutually impact using magnetic induction (B). The rotor coil generates a current in the stator coil and vice versa (Fig. 1.14b). This mutual impact means that the two electrical circuits can be connected via a common link formed by R_{Fe} and X_h, - the counter-resistance and counter-reactance. The current which the motor draws for magnetising the stator and the rotor flows through them. The voltage drop across the "common link" is called induction voltage.

Operating conditions of the motor
In the examples discussed so far, there has been no load on the motor. If the motor works within its normal operating range, the rotor frequency is lower than the frequency of the rotating field and X_2 is reduced by factor s (slip).

In the equivalent circuit diagram, the effect is described by the change in the rotor resistance R_2 by the factor of $\frac{1}{s}$.

$\frac{R_2}{s}$ can be written as $R_2 + R_2 \times \frac{1-s}{s}$ where $R_2 \times \frac{1-s}{s}$ is the mechanical load on the motor.

Values R_2 and X_2 represent the rotor. R_2 is the cause of the rotor heat loss when the motor is loaded.
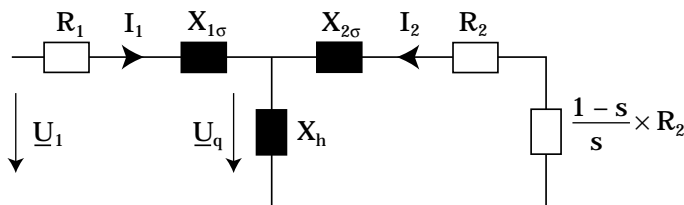

Fig. 1.15   equivalent circuit diagram for a motor under load

The slip, s, is close to zero, when the motor runs unloaded.

This means that $R_2 \times \frac{1-s}{s}$ increases.

Consequently virtually no current is able to flow in the rotor. Ideally, this is the situation in which the resistance (representing the mechanical load) is removed from the equivalent circuit diagram.

When the motor is loaded, the slip increases, reducing $R_2 \times \dfrac{1-s}{s}$.

The current, I_2, in the rotor also increases when the load is increased.

a) $\qquad s \to 0 : \dfrac{1-s}{s} \times R_2 \to \infty$

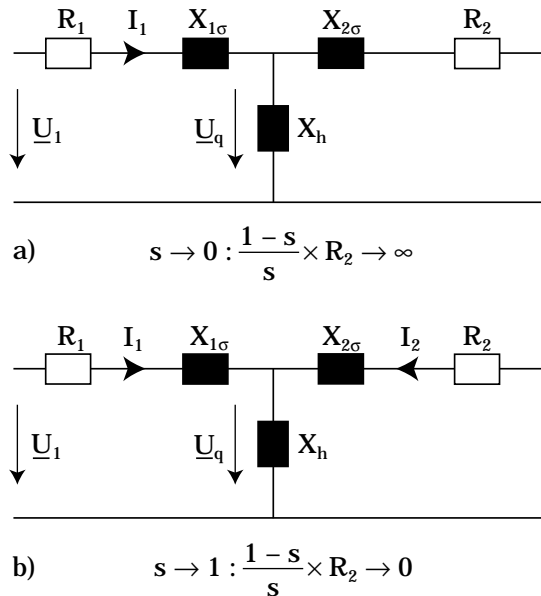b) $\qquad s \to 1 : \dfrac{1-s}{s} \times R_2 \to 0$

Fig. 1.16   Diagram of idle running (a) and blocked rotor (b)

The equivalent circuit diagram can therefore be seen to work for asynchronous motors and, in many cases, can be used to describe motor conditions.

There is a danger that the induced voltage ($\underline{U}_q$) could be mistaken for the motor terminal voltage. This is because the equivalent circuit diagram is simplified to provide a better overview of the different motor conditions. However, it should be remembered that the induced voltage only comes close to the terminal voltage when the motor is unloaded.

If the load increases, I_2 – and thus I_1 – are increased and the voltage drop needs to be considered. This is important, particularly when a motor is controlled by a frequency converter.
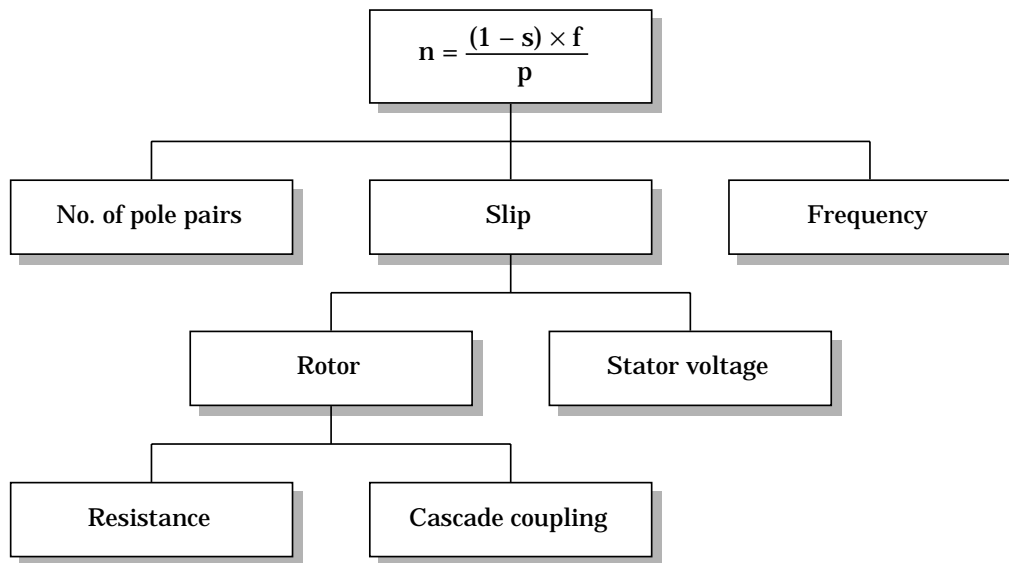
Speed change

The speed, n, of the motor is dependent on the speed of the rotating field and can be expressed as:

$$s = \frac{n_0 - n}{n_0} \quad \text{in which} \quad n = \frac{(1 - s) \times f}{p}$$

The motor speed can therefore be changed by altering:

- the number of pole pairs, p, of the motor (e.g. pole-switchable motors)
- the motor slip (e.g. slip ring motors)
- the frequency, f, of the motor supply voltage

Fig. 1.17   *Different possibilities for changing motor speed*

Changing the number of poles

The speed of the rotating field is determined by the number of pole pairs in the stators. In the case of a two-pole motor, the speed of the rotating field is 3,000 rpm for a 50 Hz mains supply.
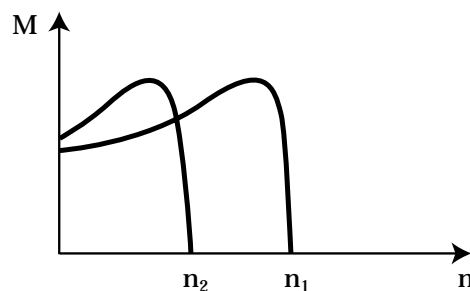
Fig. 1.18   *Pole changing motor torque characteristics*

frequency of 50 Hz, and the speed of the rotating field in a four-pole motor is 1,500 rpm.

Motors can be built for two different numbers of pairs of poles. This is because of the special layout of the stator windings in the gaps either in the form of a Dahlander winding or as two separate windings. In a motor with several poles, the types of winding are combined.

The speed is changed by switching the stator windings to change the number of pole pairs in the stator.

By switching from a small pole pair number (which generates a high speed) to a high number pole pair number, the actual speed of the motor is dramatically reduced – for example from 1,500 to 750 rpm. If the switch is made quickly, the motor runs through the generator range exerting a considerable load on the motor and the mechanics.

Slip control
Motor speed can be controlled by the slip in two different ways: either by changing the stator supply voltage or by intervening in the rotor.

Change of stator voltage
The speed of asynchronous motors can be controlled by adjusting the motor supply voltage without changing the frequency (for example using a softstarter). This is possible because the motor torque declines by the square of the voltage.
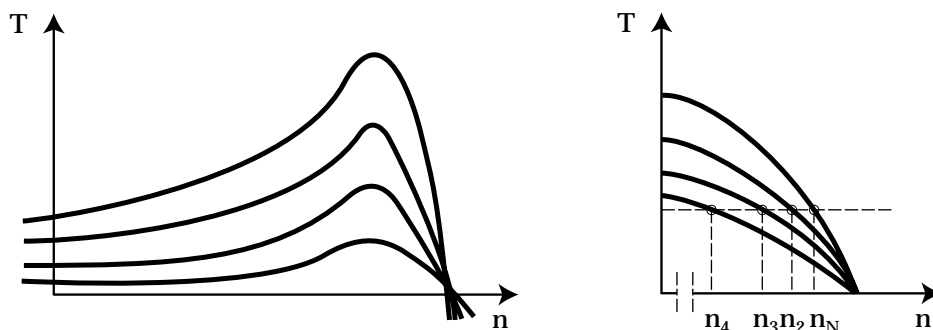
Fig. 1.19   Stator voltage (slip control) torque characteristic

As indicated by the torque characteristic, stable operating points can only be obtained in the operating range ($n_k < n < n_0$). With a slip ring motor, stable operating points can also be obtained in the ramping-up range ($0 < n < n_k$) by inserting resistors in the rotor windings.

Rotor control
There are two possible ways of intervening in the rotor. Either resistance is passed on to the rotor circuit, or the rotor circuit is connected to other electrical machines or rectifier circuits in a cascade connection.

Rotor control is therefore only possible with slip ring motors, as they are the only design where the rotor windings on the slip rings are accessible.

Changing the rotor resistors
Motor speed can also be controlled by connecting the slip rings to resistors and increasing the power loss in the rotor which leads to an increase in the slip value, and a decrease in the motor speed.

If resistors are connected to the rotor circuit, the motor's torque characteristic changes.

As shown by illustration Fig. 1.20, the stalling torque retains its value. At different settings, different speeds occur at the same load – so the pre-set speed is dependent on the load. If the motor load is reduced, the speed increases close to the synchronous speed.
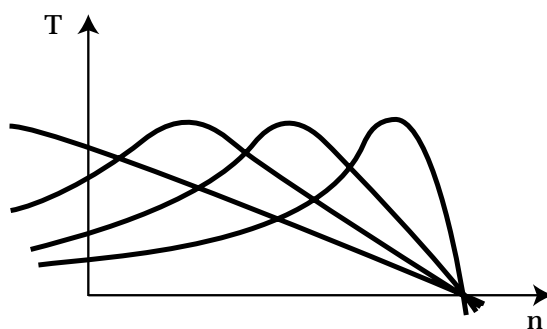
*Fig. 1.20   Rotor resistance torque characteristic*

The resistors are variable and it is important that the operating temperature is maintained.

Cascade couplings
Instead of resistors, the rotor circuit is connected via the slip rings to DC machines or controlled rectifier circuits.

DC machines provide the rotor circuit of the motor with an additional, adjustable voltage making it possible to influence the speed and magnetisation of the rotor. This technique is used mainly on electric railway systems.

Controlled rectifier circuits can be used instead of DC machines, in which case the field of application is reduced to systems with pumps, fans, etc.
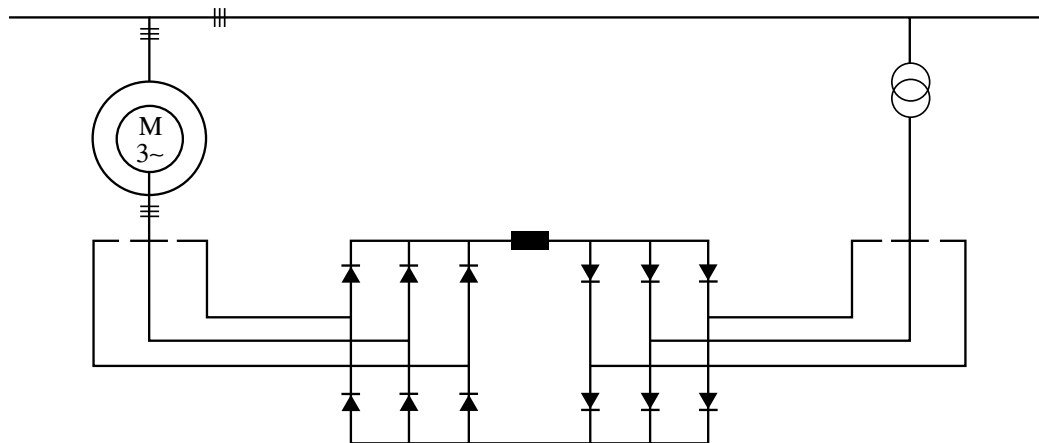
Fig. 1.21   Typical; cascade circuit

Frequency regulation

With a variable supply frequency it is possible to control motor speed without additional losses. The rotational speed of the magnetic field changes with the frequency.

The motor speed changes proportionally with the rotating field. To maintain the motor torque, the motor voltage must be changed with the frequency.

For a given load, the following applies:

$$T = \frac{P \times 9550}{n} = \frac{\eta \times \sqrt{3} \times U \times I \times \cos \varphi \times 9550}{f \times \frac{60}{p}} = k \times \frac{U}{f} \times I$$

$$T \sim \frac{U}{f} \times I$$

For a constant ratio between motor supply voltage and frequency, the magnetisation in the rated operating range of the motor is also constant.
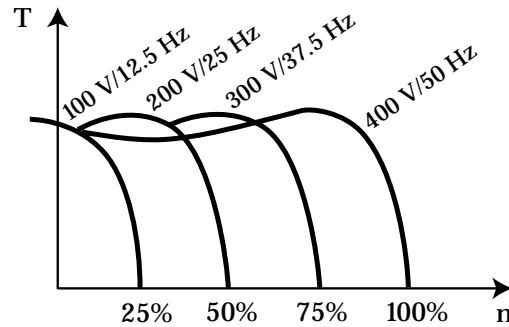
Fig. 1.22   Torque characteristic using the voltage/frequency control

In two cases, however, the magnetisation is not ideal: at the start and at very low frequencies, where additional magnetisation is required, and when operating with varying loads, where variation of the magnetisation corresponding to the load must be possible.

Fig. 1.23   Equivalent circuit diagram of the motor

Additional start-up magnetisation
It is important to look at the voltage drop $\underline{U}_s$ in connection with the induced voltage $\underline{U}_q$.

Terminal voltage: $\underline{U}_1 = \underline{U}_s + \underline{U}_q = \underline{U}_{R1} + \underline{U}_{X1} + \underline{U}_q$

Stator reactance: $X_1 = 2 \times \pi \times f \times L$

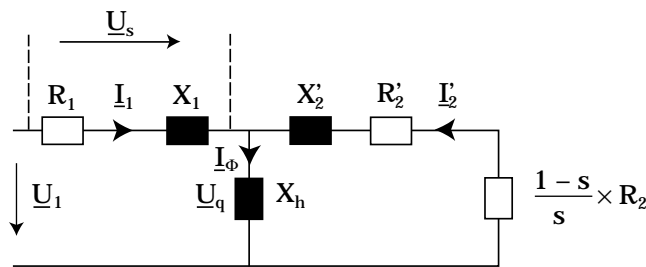The motor has been designed for its rated values. For example, the magnetising voltage, $\underline{U}_q$, can be 370 V for a motor, at $U_1 =$ 400 V and f = 50 Hz. This is where the motor has its optimum magnetisation.

The voltage-to-frequency ratio is: $\frac{400}{50} = 8 \; \frac{[V]}{[Hz]}$

If the frequency is reduced to 2.5 Hz, the voltage will be 20 V. Because of this lower frequency, the stator reactance, X_1, also becomes smaller. The voltage drop is determined only by R_1 and has no influence on the total voltage drop in the stator. R_1 corresponds approximately to the rated values, roughly 20 V, since the motor current is determined by the load.

The terminal voltage now corresponds to the voltage drop across the stator resistor, R_1. There is no voltage for magnetising the motor and the motor is not able to generate a torque at low frequencies if the voltage-to-frequency ratio is kept constant throughout the range. Consequently, it is important to compensate for the voltage drop during start-up and at low frequencies.

Load-dependent magnetisation
After adapting the motor with the extra magnetisation at low frequencies and during start-up, over-magnetisation will occur if running with a small load. In this situation, the stator current, I_1, will decline and the induced voltage, $\underline{U}_q$, will increase.

The motor will take up a higher reactive current and become unnecessarily heated. Magnetisation thus depends on the voltage to the motor changing automatically in response to motor loads.

For optimum motor magnetisation the frequency and the varying load must be taken into account.

Motor data

All motors have a permanent nameplate which lists all essential data, further data is usually available in the motor catalogue.
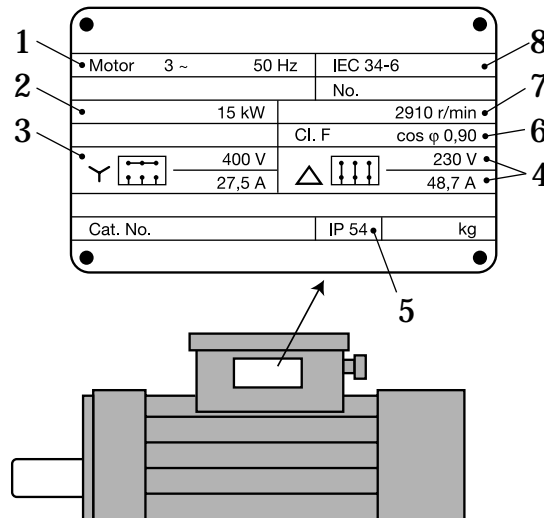

Fig. 1.24   The motor nameplate

Example

The nameplate for a two-pole 15 kW motor may have the following data:

1. The motor has three phases and is for a mains supply with a frequency of 50 Hz.

2. The rated output of the motor is 15 kW, i.e. the motor is able to supply a shaft output of at least 15 kW if connected to the mains supply as indicated. The rated output of the asynchronous motor has been written into a standard. This allows the user a free choice of the different motor makes for various applications. The standard series has output levels such as:

kW	0.06	0.09	0.12	0.18	0.25	0.37	0.55	0.75	1.10	1.50	2.20	3.00
kW	4.00	5.50	7.50	11.0	15.0	18.5	22.0	30.0	37.0	45.0	55.0	75.0

Table 1.02 Motor output series

Horsepower (HP) is not now a commonly used unit for measuring motor output and it can be converted as follows:
1 HP = 0.736 kW.

3-4. The stator windings can be connected in a "star" or "delta" formation.

If the mains voltage is 400 V, the windings must be connected in a "star" formation. The motor current is then 27.5 A per phase. If the mains voltage is 230 V, the windings must be connected in a "delta" formation. The motor current is then 48.7 A per phase.

At start-up, when the current is between 4 and 10 times higher than the rated current, the mains supply may be overloaded. This has led supply companies to issue regulations ordering the start-up current of large motors to be reduced. This can be achieved by, for example, having the motor start up in a star connection and subsequently switching to a delta connection.
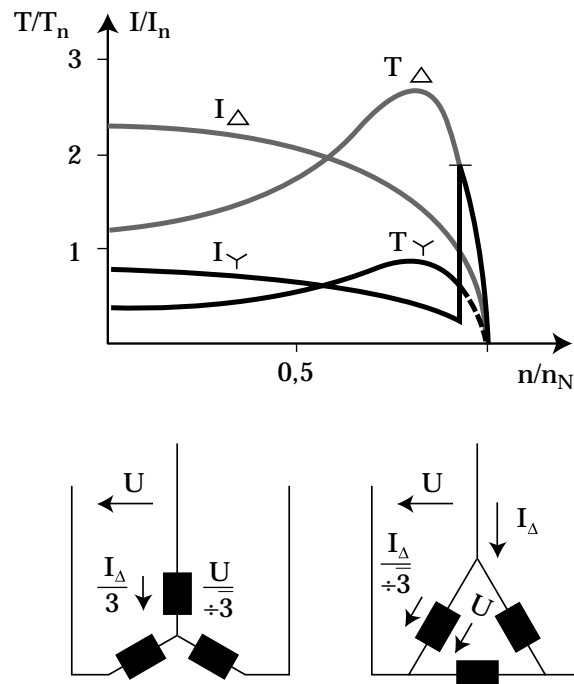

Fig. 1.25   Motor torque and current in star (γ) and delta (Δ) connections

With the star connection power and torque are reduced to $1/3^{rd}$, and the motor cannot start at full load.
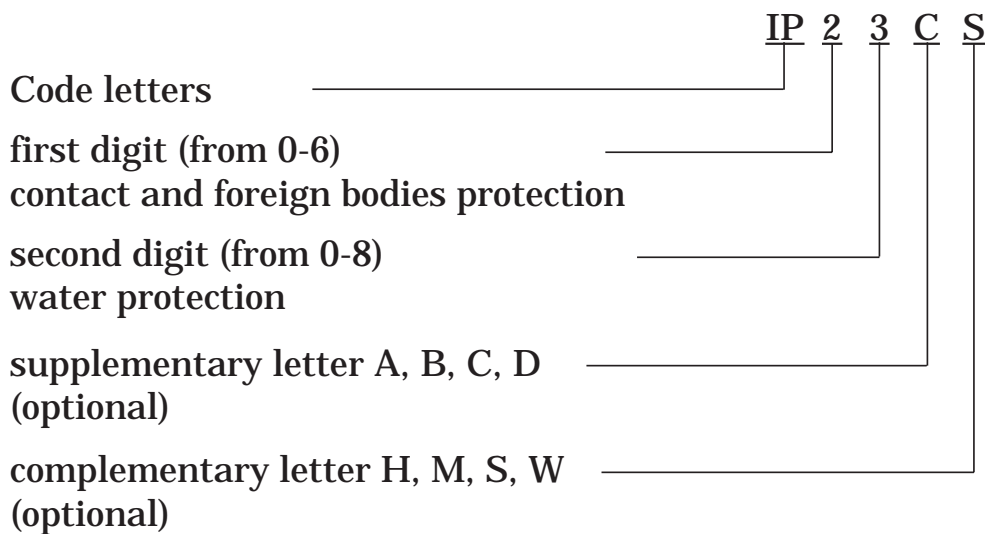
A motor designed for star connection will be overloaded if there is no switch-over to star connection for full-load operation.

5. The motor protection rating indicates the degree of protection provided by the motor enclosure against the penetration of liquids and foreign bodies.

   Fig. 1.26 gives the designations used in the international standard IEC Publication 34-5.
   Protection is indicated by the two letters IP (International Protection) and two digits.
   These are used to specify the protection level against contact and foreign bodies (first digit), and as liquid (second digit). If required, extra letters can be added. The basic layout of the IP code is as follows:

   <div align="right"><u>IP</u> <u>2</u> <u>3</u> <u>C</u> <u>S</u></div>

   Code letters

   first digit (from 0-6)
   contact and foreign bodies protection

   second digit (from 0-8)
   water protection

   supplementary letter A, B, C, D
   (optional)

   complementary letter H, M, S, W
   (optional)

   You should also note that:

   - If a digit does not have to be stated, it can be replaced by the letter "X".
   - Supplementary and/or complementary letters can be removed without being replaced by anything else.
   - If more than one complementary letter is required, the alphabetical sequence must be followed.

Digit	first digit		second digit
	Contact protection	Foreign body protection	Water protection
0	no protection	no protection	no protection
1	protection against contact with the back of the hand	protection against solid foreign bodies with 50 mm dia.	protection against vertically dripping water
2	protection against contact with the fingers	protection against solid bodies 12.5 mm dia.	protection against water dripping at a slope (15°)
3	protection against contact with tools	protection against solid foreign bodies with 2.5 mm dia.	protection against water sprayed to an angle of 60° angle
4	protection against contact with a wire	protection against solid foreign bodies with 1.0 mm dia.	protection against water sprayed from all directions
5	protection against contact with a wire	dust protection	protection against beamed water
6	protection against contact with a wire	dust protection	protection against strongly beamed water
7	–	–	protection against temporary sub-mersion in water
8	–	–	protection against permanent sub-mersion in Water

Fig. 1.26   Listing of the protection of motors under IEC 34-5

The optional supplementary letter indicates that people are protected against access to hazardous components:
- Back of hand   Letter A
- Finger   Letter B
- Tools   Letter C
- Wire   Letter D

The optional complementary letter indicates that operating plant is protected and provides complementary information especially on:
- High-voltage units   Letter H
- Water test during operation   Letter M
- Water test during standstill   Letter S
- Weather conditions   Letter W

In case of operating plant protected against dust (first digit is 5), dust penetration is not completely prevented; however, dust is only allowed to enter in limited quantities and the unit will continue to operate without interfering with safety.

Water protection is offered up to digit 6, which means that the requirements for all lower numbers have also been ful-

filled. An operating unit with the designation IPX7 (temporary submersion) or IPX8 (permanent submersion) need not necessary also comply with the requirements concerning protection against water jets IPX5 or strong jets of water IPX6. If both requirements are to be fulfilled, the operating unit must be given a double designation to cover both, e.g. IPX5/IPX7.

Example: IP 65 says that the motor is contact-safe and holds tight against dust and water jets.

6. The rated current, I_s, which the motor takes up, is called apparent current and can be divided into two: an active current I_w and a reactive current I_B. Cos φ indicates the share of the active current as a percentage of the motor current at rated operation. The active current is converted into shaft output, while the reactive current indicates the power required to build up the magnetic field in the motor. When the magnetic field is subsequently removed, the magnetising power will be fed back to the mains supply.

The word "reactive" indicates that the current moves to and from the wires without contributing to the shaft output.

The apparent current input to the motor from the mains is not determined by simply adding the active current to the reactive current; this is because these two currents are displaced in time. The size of this displacement depends on the frequency of the supply network. At a frequency of 50 Hz, the displacement between the current is 5 milliseconds. A geometrical summation is thus required:

$$I_S = \sqrt{I_W^2 + I_B^2}$$

The currents can be seen as the sides of a right-angled triangle, where the long side equals the square root of the sum of the short sides squared (following Pythagoras's geometry).

φ is the angle between the apparent current and the active current and Cos φ is the ratio between the size of the two currents:

$$\cos \varphi = \frac{I_W}{I_S}$$

Cos φ can also be shown as the ratio between the actual output P and the apparent output S:
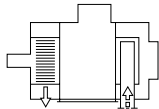
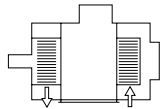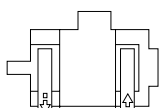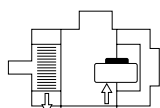$$\cos \varphi = \frac{P}{S}$$
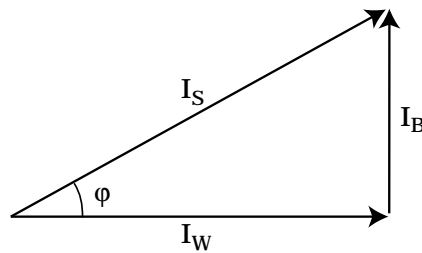
Fig. 1.27   Connection between apparent, reactive and active

The phrase "apparent power" means that only part of the apparent current generates power, i.e. the part termed I_w, the active current.

7.   The rated speed of the motor is the motor speed at rated voltage, rated frequency and rated load.

8.   Electric motors are designed for different types of cooling. Normally the cooling method is stated in accordance with international standard IEC Publication 34-6.

Fig. 1.28 shows the designations of this standard and IC stands for International Cooling.

IC01 **Self-ventilated** The inside of the motor is cooled directly by the surrounding air		IC17 **Externally ventilated** Motor with built-on fan for cooling air input	
IC06 **Externally ventilated** Motor for separate cooling air input		IC37 **Externally ventilated** Motor for separate cooling air output and separate cooling air input	

Fig. 1.28   Motor cooling in accordance with IEC 34-6

Motor selection must be determined by the application as well as the installation.

The international standard IEC 34-7 gives the mounting type of the motor in the form of two letters, IM (International Mounting) and four digits and Fig. 1.29 shows some of the most common designs.

Using the data from the motor nameplate, other motor data can be calculated for example, the rated torque of the motor can be calculated from the following formula:

$$T = \frac{P \times 9550}{n} = \frac{15 \times 9550}{2910} = 49 \text{ Nm}$$

Machines with end plates, horizontal design							
Mounting			Explanation				
Fig.	Abbreviation according to DIN 42 950	DIN IEC 34 Part 7 Code I	Code II	End plate	Stator (housing)	General design	Attachment or mounting
	B 3	IM B 3	IM 1001	2 end plated	w/feet	–	Mounting on base
	B 3/B 5	IM B 35	IM 2001	2 end plates	w/feet	Attachment flange	Mounting on base with extra flange
	B 3/B 14	IM B 34	IM 2101	2 end plates	w/feet	Attachment flange	Monting base with extra flange
	B 5	IM B 5	IM 3001	2 end plates	ohne Füße	Attachment flange	Flange mounting
	B 6	IM B 6	IM 1051	2 end plates	w/feet	Mounting B3, end plates turned 90°	Attachment to wall feet left seen from drive side

Fig. 1.29   Motor mounting according to IEC 34.7

The efficiency η of the motor can be determined as the ratio between the power rating and the electrical input power:

$$\eta = \frac{P}{\sqrt{3} \times U \times I \times \cos \varphi} = \frac{15000}{\sqrt{3} \times 380 \times 29 \times 0.9} = 0.87$$

The motor slip can be calculated, since the nameplate gives the rated speed and frequency. These two data items indicate a two-pole motor which has a synchronous speed of 3,000 rpm.

The slip speed (n_s) is thus 3,000-2,910 = 90 rpm.

The slip is normally stated as a percentage:

$$s = \frac{n_s}{n_0} = \frac{90}{3000} = 0.03 = 3\%$$

Of course the motor catalogue contains some of the nameplate data. In addition other data is given as well:

Type	Output	Speed	Effici-ency	cos φ	Current at 380 V	$\frac{I_a}{I}$	T	$\frac{T_a}{T}$	$\frac{T_{max}}{T}$	Torque of inertia	Weight
	kW	min⁻¹	%		A		Nm			kgm²	kg
160 MA	11	2900	86	0.87	25	6.2	36	2.3	2.6	0.055	76
160 M	15	2910	88	0.90	29	6.2	49	1.8	2.0	0.055	85
160 L	18.5	2930	88	0.90	33	6.2	60	2.8	3.0	0.056	96

Fig. 1.30   The motor catalogue contains additional data

Shaft output, speed, cos φ and motor current can be taken from the nameplate. Efficiency and torque can be calculated on the basis of the nameplate information.

Furthermore, the motor catalogue says that the starting current of the 15 kW motor, I_a, is 6.2 times higher than the rated current, I_N. $I_a = 29 \times 6.2 = 180$ A.

The starting torque of the motor (T_a) is stated to be 1.8 times the rated torque $T_a = 1.8 \times 49 = 88$ Nm. This starting torque requires a starting current of 180 A. The maximum torque of the motor, the stalling torque (T_K) is twice the size of the rated torque: $T_k = 2 \times 49 = 98$ Nm.
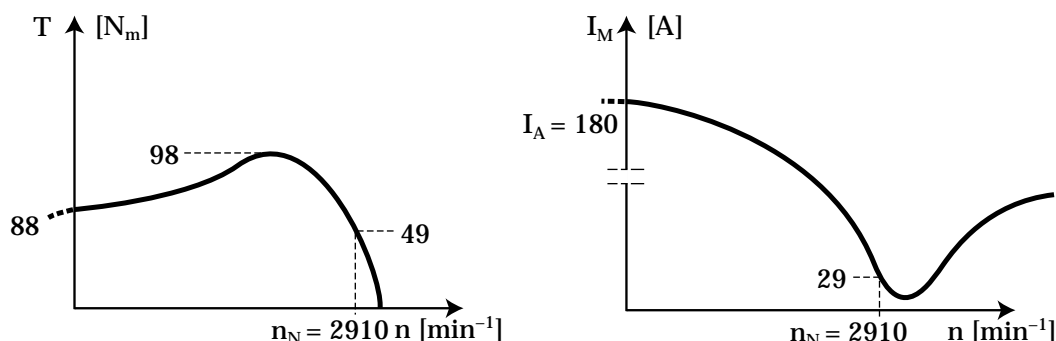

Fig. 1.31   Motor torque and current

Finally, the moment of inertia and the weight of the motor are stated on the motor nameplate. The moment of inertia is used for calculating the acceleration torque. The weight may be of significance in connection with transportation and installation.

Some motor manufacturers do not publish the moment of inertia, and use the flywheel effect WR^2 instead. However, this value can be converted as follows:

$$J = \frac{WR^2}{4 \times g}$$

g is the acceleration due to gravity
The unit for the flywheel effect WR^2 is [Nm^2]
The unit for the moment of inertia J is [kgm^2]

Types of load

When the motorshaft torque is equal to the torque exerted by the load, the motor is stationary. In such cases the torque and the speed are constant.

The characteristics for motor and machine are stated as the ratio between speed and torque or output. The torque characteristics have already been discussed. The characteristics of the machine can be divided into four groups.
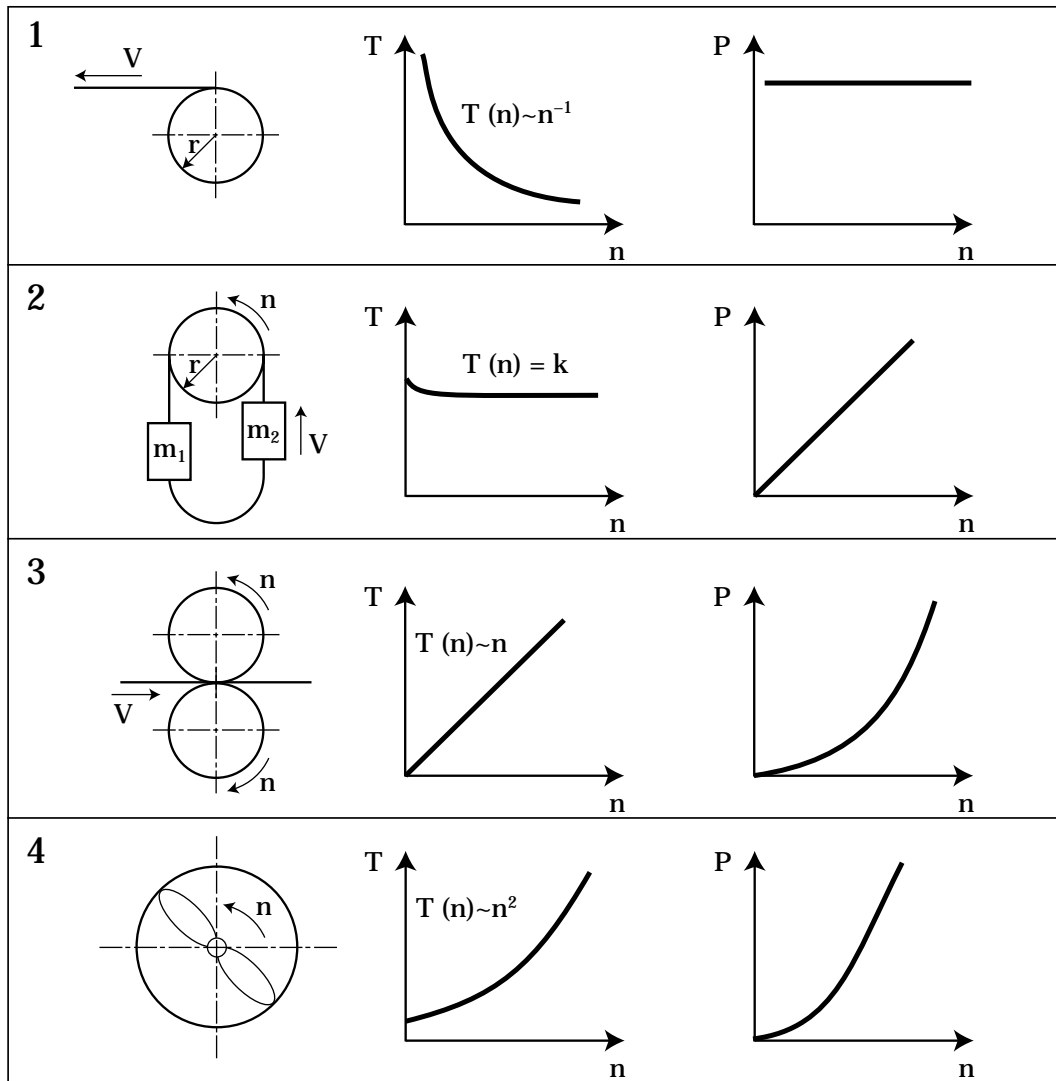
Fig. 1.32   Typical load characteristics

The first group (1) consists of machines for winding material under tension. This group includes, for example veneer cutting machines and machine tools.

Group (2) consists of conveyor belts, cranes, positive displacement pumps as well as machine tools.

Group (3) consists of machines such as rollers, smoothing machines and other processing machines.

Group (4) comprises machines operating by centrifugal force, such as centrifuges, centrifugal pumps and fans.

The stationary state occurs when motor and machine torque are identical (Fig. 1.33). The graphs cross each other at point B.

When a motor is sized for a given operating machine, the intersection point should be as close as possible to point N for the rated motor data.

A surplus torque should be available throughout the range, from standstill to the intersection point. If that is not the case, operation becomes unstable and the stationary state may change if the speed is too low. One of the reasons for this is that the surplus torque is required for acceleration.
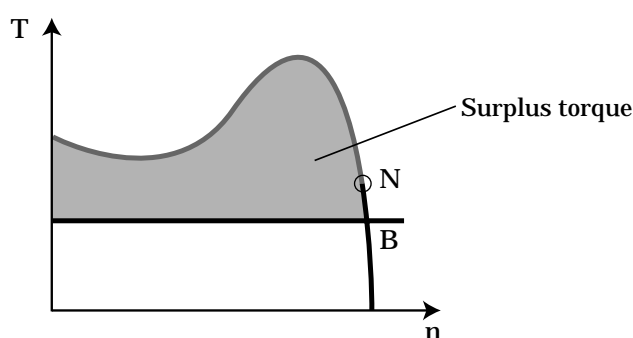
Fig. 1.33   The motor needs a surplus torque for acceleration

In particular for machines in groups 1 and 2, it is necessary to take account of this starting condition. These types of load may have an initial starting torque which is same size as the starting torque of the motor. When the starting torque of the load is higher than the starting torque of the motor, the motor cannot start.
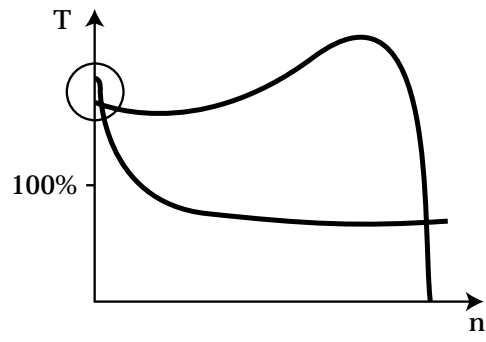
Fig. 1.34   The starting state may call for a particularly high torque
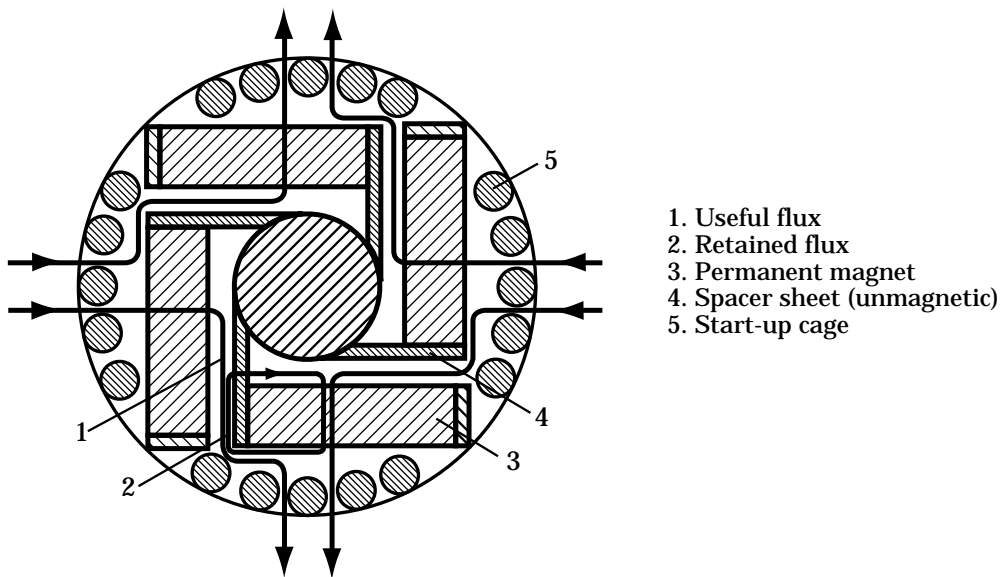
Synchronous motors

The stator build-up of synchronous and asynchronous motors is the same.

The rotor of the synchronous motor (also called a magnet wheel) has salient magnetic poles and can be built either with permanent magnets (for small motors) or electromagnets.

The rotor has two or more pairs of poles and can thus also be used for low-speed motors. A synchronous motor is not able to start using just the mains supply. This is because of the rotor inertia and the high speed of the rotating field. The rotor must therefore be brought to the same speed as the rotating field.

For larger motors this is usually done using a pony motor or a frequency converter.

Small motors are normally started using starting windings (damping windings) which cause the motor to behave as a squirrel-cage motor.

1. Useful flux
2. Retained flux
3. Permanent magnet
4. Spacer sheet (unmagnetic)
5. Start-up cage

Fig. 1.35   (Synchronous motor rotors: permanent magnet)

After start-up, the motor turns synchronously with the rotating field. If the motor is subjected to a load, the distance between the rotor poles and the rotating field poles increases. The rotor stays behind the rotating field by the load angle (v) and thus behind the no-load position of the rotor (Fig. 1.35).

Synchronous motors have a constant speed which is independent of the load. The motor will not tolerate a higher load than the starting power between rotor and magnetic field.

If the load exceeds this starting power, the synchronism is inter-
rupted and the motor stops.

Synchronous motors are used for example, in parallel opera-
tions where several mechanically independent units are to be
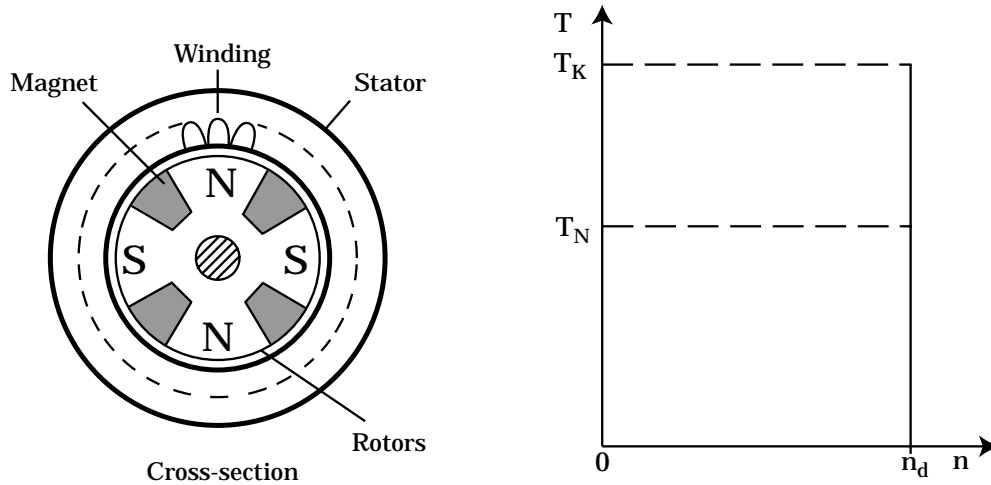operated synchronously.

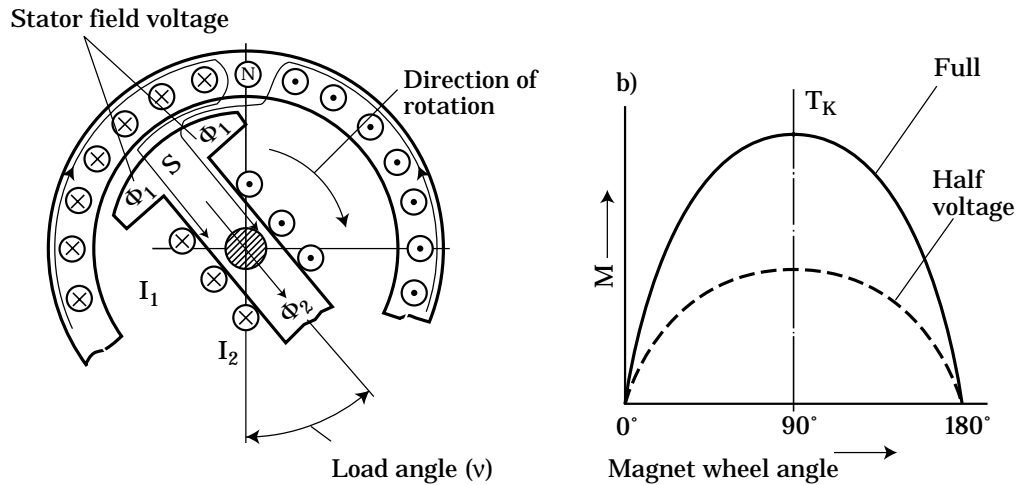*Fig. 1.36   Rotor with salient poles and torque characteristics*

*Fig. 1.37   Loading angle and operating torque as opposed to
   rotor angle*

Reluctance motors

Three-phase AC reluctance motors develop speed like normal squirrel cage three-phase asynchronous motors, but then become synchronous. Since reluctance motors have a simple squirrel cage winding in the rotor, they are sturdy, reliable, maintenance-free, do not generate radio interference and are relatively low-priced. The disadvantages are that they have a high inductive reactive output requirement and that they are inefficient which is why reluctance motors are only generally used by industry up to an output of about 15 kW.

Build-up

The stators of a three-phase AC reluctance motor are the same as a normal three-phase squirrel cage AC asynchronous motor and the rotor.

It has a simple squirrel cage winding. However, the rotor of a reluctance motor has the same number of salient poles as it has stators. The poles are made by cutting pole holes at the circumference of the rotor metal plate set or similar plate structures (see Fig. 1.38a).

cross-section, rotor
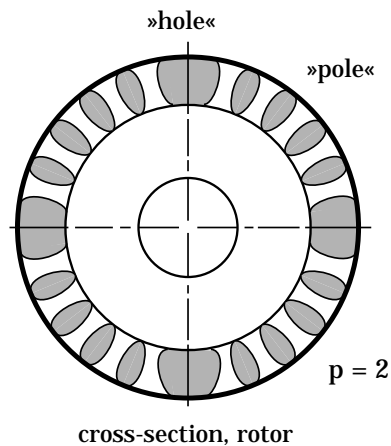
Fig. 1.38a Reluctance rotor

A flexible, magnetic resistance (reluctance) occurs at the rotor circumference through the pole holes, which can be filled with the same material the rotor cage the resistance is smallest in the pole area and largest at the pole gap area.
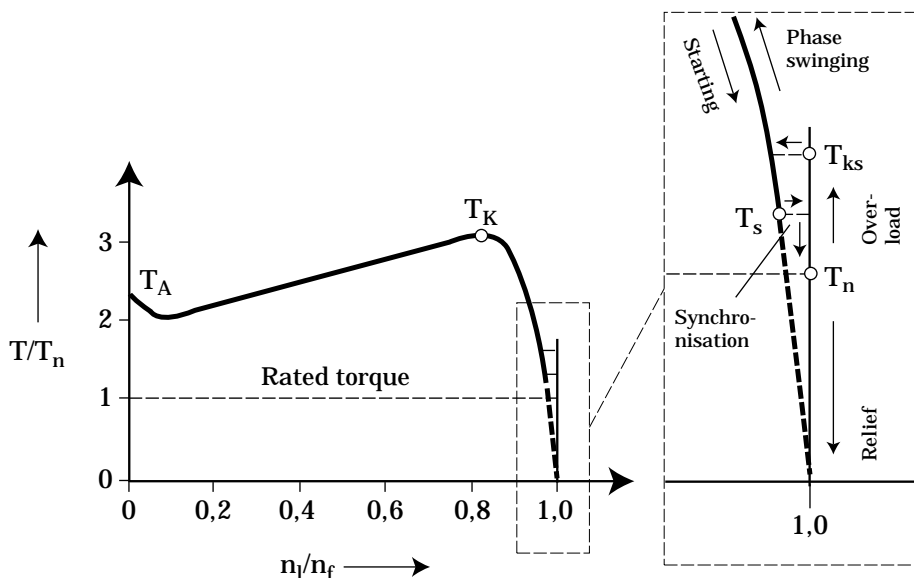
Fig. 1.38b Torque graph of a reluctance motor

When connected to the three-phase AC supply, reluctance motors – just like normal squirrel-cage motors – develop a torque and run up close to the synchronous speed value, provided the motor torque is higher than the load torque throughout the run-up process. The starting current is normally somewhat higher and the starting torque somewhat smaller than in comparable squirrel-cage motors, since there is a wider air gap in the pole gap area. When the rotor has practically reached the speed of the rotating field, the magnetic coupling of stator rotating field and rotor poles results in a synchronisation torque (reaction torque) that drives the rotor into synchronous operation. After this synchronisation process, the motor will run at synchronised speed despite falling rotor regulation.

A synchronised reluctance motor works in more or less the same way as a synchronous motor and its rotor turns synchronically with the speed of the stator rotating field. In the same way as the pole of the stator rotating field moves to affect the rotor poles, in the reluctance motor the magnetic flux of the stator rotating field tries to activate the rotor in the area of the salient poles. The small air gap at these points results in a smaller magnetic resistance than in the area of the pole gaps. The effort of the magnetic flux not to have to overcome the higher magnetic resistance in the area of the pole gaps creates a synchronous torque which it maintains under load.

Because of the falling DC generation in the rotor, the synchronous torque of a reluctance motor is considerably lower than that of a comparable synchronous motor.

When synchronisation has been completed, reluctance motors have operational characteristics similar to standard synchronous motors. The rotor turns at the speed of the stator rotating field, which depends on the mains frequency and the number of pairs of poles.

The load angle determines how far the salient rotor poles remain behind the stator rotating field. If the motor is overloaded phase swinging occurs and it runs as an asynchronous motor with a load-dependent speed (Fig. 1.38b). The motor resynchronises when the load torque is lower than the synchronising torque. If, however, the motor receives a load higher than its asynchronous stalling torque, it will stop.

Because of the increased air gap in the area of the pole gaps in the circumference of the rotor, reluctance motors have relatively high dispersion, which leads to a high inductive reactive power requirement and a corresponding share. This leads to a low power factor, of between 0.4 and 0.5 of rated operation. When designing drives with reluctance motors, this reactive power requirement must be taken into account.

Three-phase AC reluctance motors are used mainly in multi-task applications where the speed of each axis needs to be exactly the same and where the use of a single motor with mechanical transmission to each axis would be too difficult or too expensive.

Examples of such uses could be drives for spinning machines, pumps or conveyor systems.

0. Introduction

A static frequency converter is an electronic unit which provides infinitely variable control of the speed of three-phase AC motors by converting fixed mains voltage and frequency into variable quantities. Whilst the principle has always remained the same, there have been many changes from the first frequency converters, which featured thyristors, to today's microprocessor-controlled, digital units.

Because of the ever-increasing degree of automation in industry, there is a constant need for more automatic controls, and a steady increase in production speeds and better methods to further improve the efficiency of production plants are being developed all the time.

Today electric motors are an important standard industrial product. These motors are designed to run at a fixed speed and work has been going on for many years to optimise the control of their running speed.
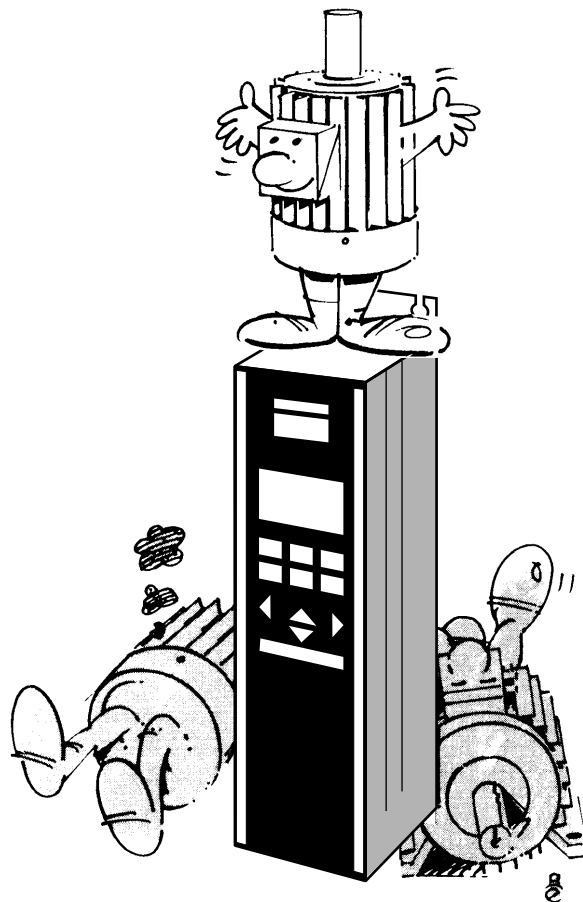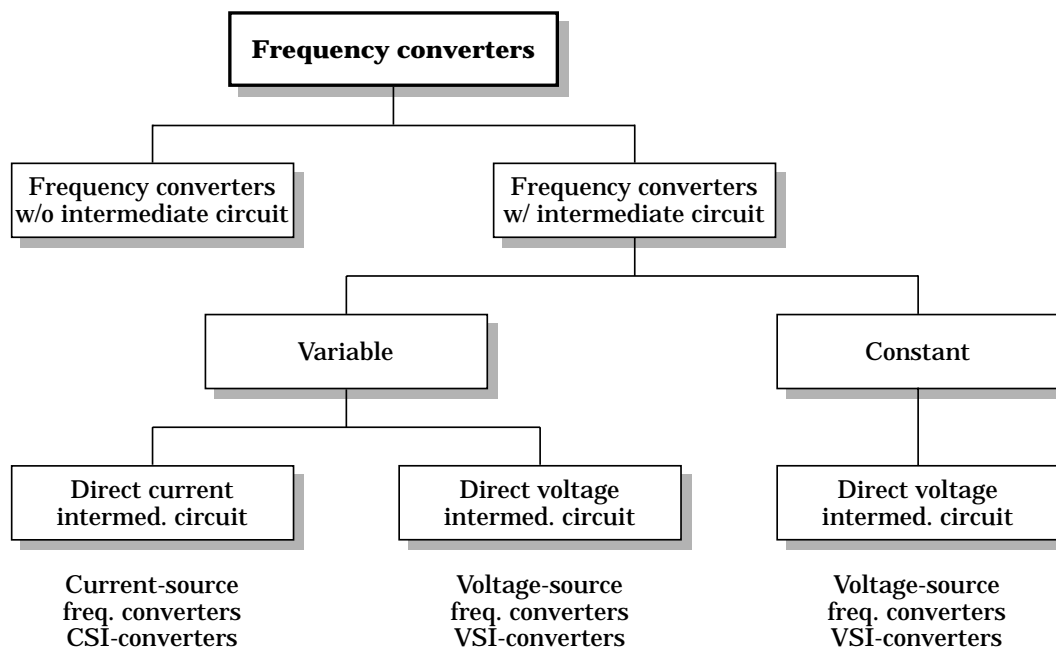

Fig. 0.01

It was not until the static frequency converter was introduced that three-phase AC motors with infinitely variable speed could be used effectively.

The vast majority of the static frequency converters used by industry today to control or regulate the speed of three-phase AC motors are designed according to two different principles (Fig. 0.02):
• frequency converters without an intermediate circuit (also known as direct converters), and
• frequency converters with a variable or constant intermediate circuit.

Fig. 0.02   Converter principles

Frequency converters with an intermediate circuit have either a direct current intermediate circuit or a direct voltage intermediate current and are called current-source inverters and voltage-source inverters.

Intermediate circuit inverters offer a number of advantages over the direct inverter, such as:
• better reactive current control
• reduction of harmonics
• no limitations with respect to output frequency (but there is a limitation to the control and properties of the electronic components used. Frequency converters for high output frequencies are mostly intermediate circuit inverters.)

Direct inverters tend to be slightly cheaper than intermediate circuit inverters, though they typically suffer from poorer reduction of harmonics.

As most frequency converters use a DC voltage intermediate circuit, this book will focus mainly on this group of converters.

Advantages of infinitely variable speed adjustment

Today, the frequency converter controlled, three-phase AC motor is a standard element in all automated process plants. Apart from its ability to use the good properties of three-phase AC motors, infinitely variable speed regulation is often a basic requirement because of the design of the plant. In addition, it offers a number of further advantages:

Energy savings
Energy can be saved if the motor speed matches requirements at any given moment in time. This applies in particular to centrifugal pumps and fan drives where the energy consumed is reduced by the cube of the speed. A drive running at half speed thus only takes 12.5% of the rated power.
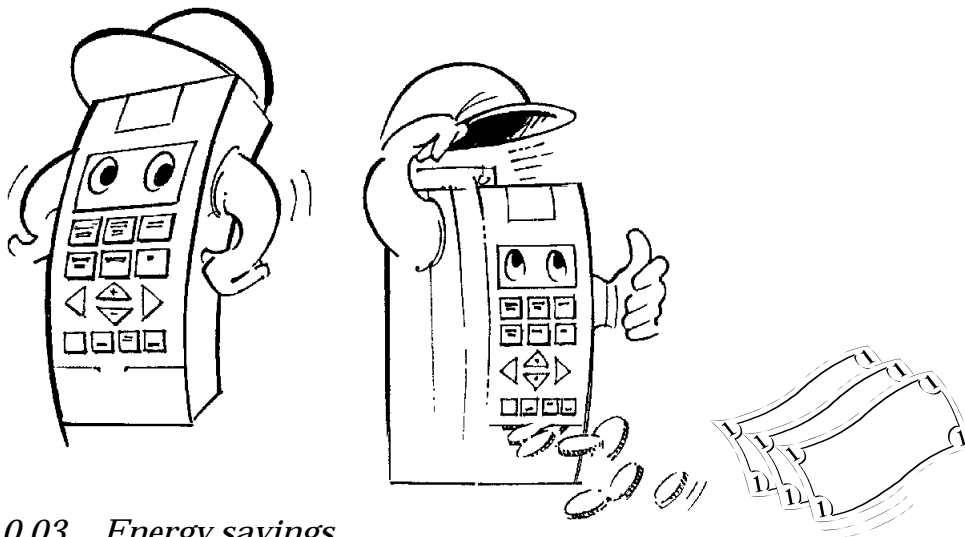
Fig. 0.03   Energy savings

Process optimisation
Adjusting the speed to the production process offers a number of advantages. These include increasing production, while reducing rejection rates and decreasing material consumption and wear.

Smooth machine operation
The number of starts and stops with full speed change can be dramatically reduced. Using soft start-up and stop ramps, shocks and impacts on the machine components can be avoided.

Less maintenance
A frequency converter requires no maintenance. When used to control motor's, the life-time of plants can be increased. For example, in water supply systems, the water hammer that occurs with direct mains connection of the pump motors disappears, and damage to the water pipes is avoided.

Improved working environment
The speed of conveyor belts can be matched exactly to the required working speed. For example, bottles on the conveyor belt in a bottle filling line make much less noise if the belt speed can be reduced when the bottles are queuing.
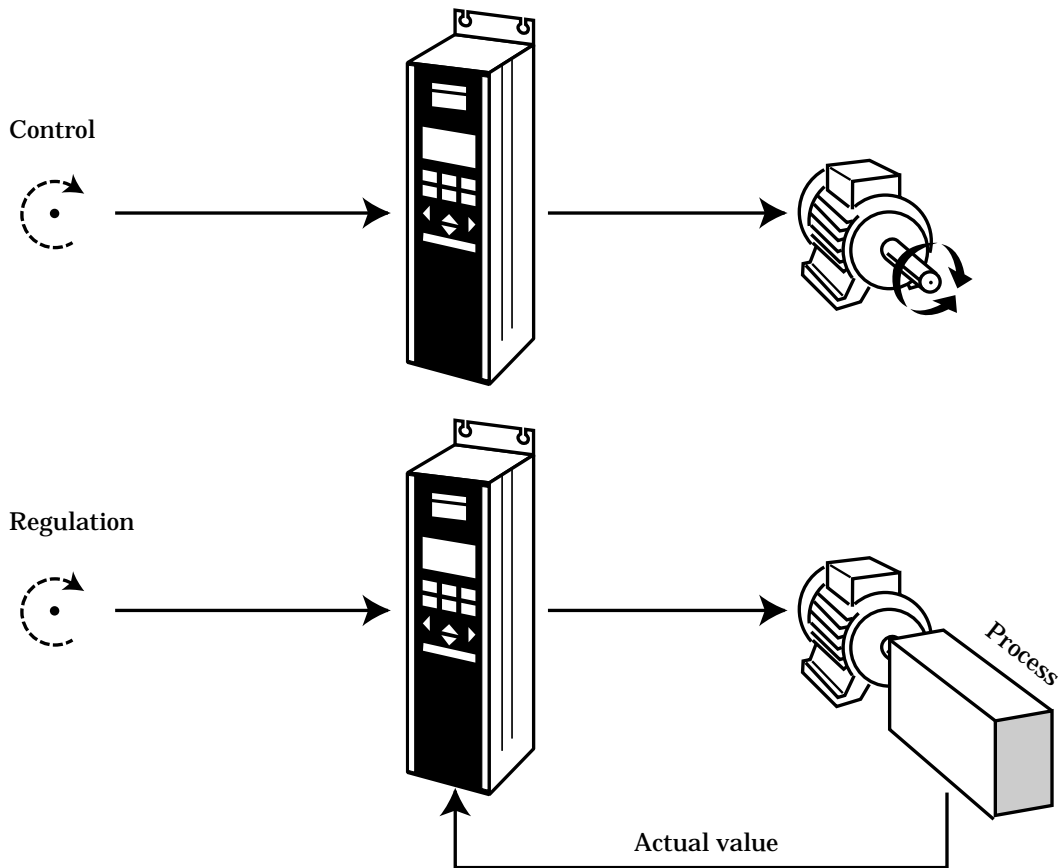
If the speed of a fan is adjustable, unnecessary noise near the fan can be reduced, as can the draught.
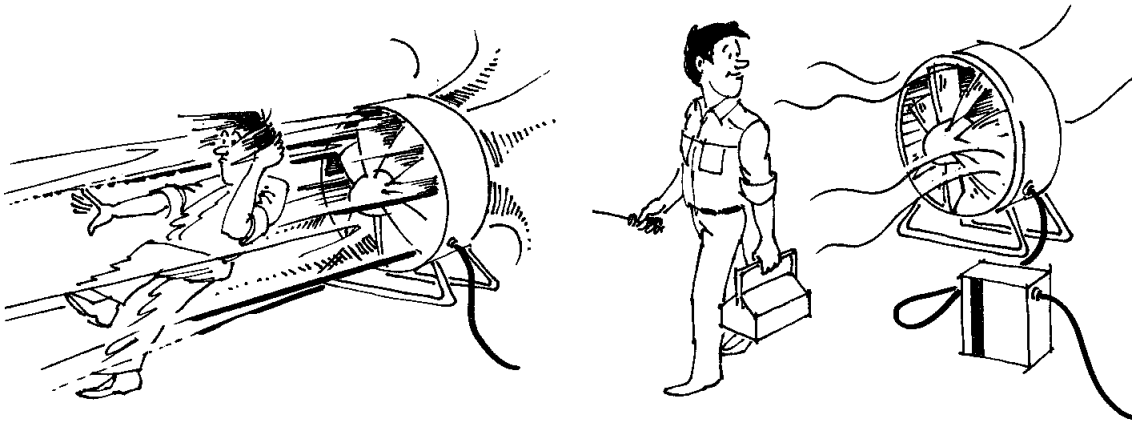
Fig. 0.04   Improved working environment

Control or regulation?

Many people use the terms 'control' and 'regulation' interchangeably. However, they do have precise definitions – largely as a result of developments in the field of automation.

Fig. 0.05   Distinction between control and regulation

The terms "control" and "regulation" depend on the type of plant. With speed "control" a signal which is expected to produce the required speed is sent to the motor. With speed "regulation" a feedback signal is given from the process. If the speed does not correspond to the requirements, the signal to the motor is regulated automatically until the motor speed is as it should be.