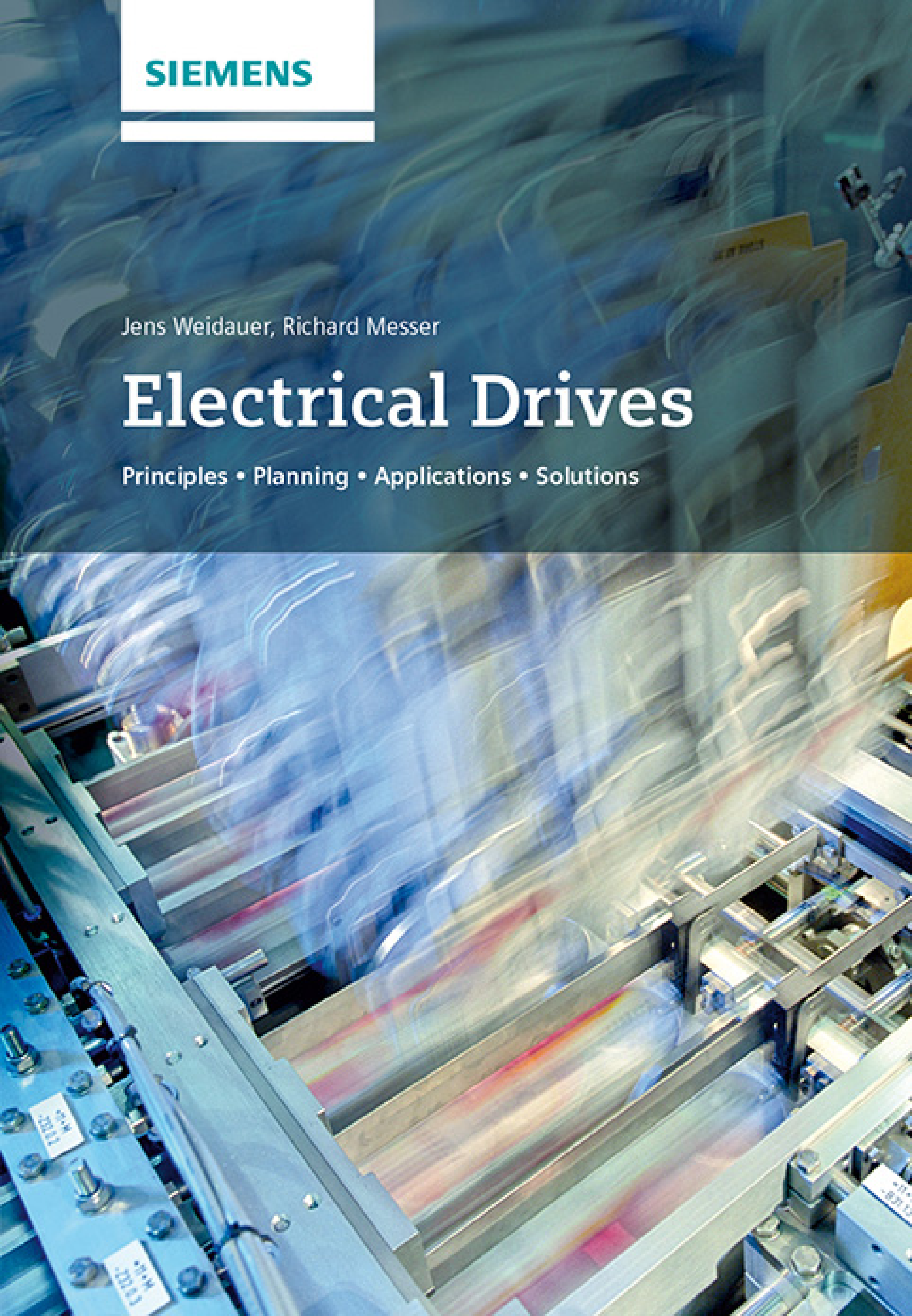

SIEMENS

Jens Weidauer, Richard Messer

Electrical Drives

Principles • Planning • Applications • Solutions

Weidauer/Messer
Electrical Drives

Electrical Drives

Principles · Planning · Applications · Solutions

by Jens Weidauer
and Richard Messer

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Foreword

Electrical drives are the most important source of mechanical energy in machines and industrial plant. In our modern world, they ensure that motion can take place, and that transport and manufacturing processes are possible at all. Although the technical field of electrical drives is over 100 years old, today it is more dynamic and diverse than ever.

It starts with the electric motors themselves, the heart of all electrical drives. Today, they are not only available in the widest range of designs and power classes – from standard motors for direct-on-line operation to highly-efficient servo motors – but they also distinguish themselves through their ever more ingenious design principles and use of novel materials. Smaller, lighter, and more efficient electric motors give designers new degrees of freedom, pushing ahead the development of machines, plant equipment, and electrical vehicles.

Drive controllers are also becoming more powerful and smaller due to fast, low-loss switching power semiconductors, faster microprocessors, as well as modern manufacturing technologies. In combination with innovative electrical motors, the torque, speed, and position of electrical drives can today, at any given time, be set exactly as required by the manufacturing or transport process. In many instances, the controller and electric motor are brought together and combined in one device. In particular, electromobility is driving the development of real mechatronic systems, in which gearbox, electric motor, and drive controller merge together to provide customised drive solutions.

As part of a modern automation solution, electrical drives must be universally coordinated. To enable this, they are equipped with communication interfaces as well as integrated control, safety, and diagnostic functions going well beyond those of the classic drive controller. These allow the planner to implement the required coordination functions centrally, distributed, or in the drive itself.

Through both technical advancements and increasingly finer adaptations for special requirements, the wealth of types of electrical drives will continue to increase. Good orientation in the world of electrical drives is therefore indispensable for both decision makers and designers. This book provides this. Both the principles as well as the application of electrical drives are presented systematically and clearly. This comprehensive overview will benefit the reader and provide added confidence when evaluating drive solutions.

Now in its third edition, this “standard work of electrical drives” will continue to broaden the knowledge of electrical drives, and for many technicians be a useful guide when designing efficient machines, plant equipment, and electrical vehicles.

Prof. Dr. Siegfried Russwurm
Member of the Managing Board of Siemens AG

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1 Electrical drives at a glance

1.1 A short history of electrical drives

Electrical drives convert electrical energy into mechanical energy and serve as the intermediary between the electrical supply system, the energy source, and the driven machine, the energy consumer.

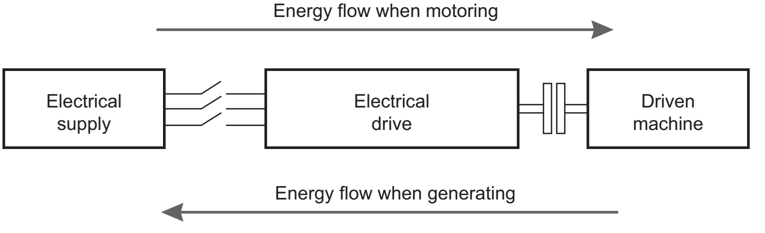

Figure 1.1 Electrical drives as the intermediary between the electrical supply system and the driven machine

Due to their central position in the energy chain flow, electrical drives have become a key component in industrial applications, as well as in transportation and in consumer goods. In many areas, they have driven technical development and have themselves been the focus of numerous developments.

The core component of every electrical drive is the motor. The physical laws, upon which the motor is based, were discovered in the early 19th century.

Discovery of the principles 1820 to 1875

In 1820, Hans Christian Oerstedt discovered that when a magnetic needle is suspended close to a current carrying conductor, it is deflected. In the same year, André Marie Ampère made his fundamental discoveries of the interaction between electrical currents and magnetic fields. These discoveries led to the development of a large number of "electromagnetic machines", whose practical application, however, were limited due to the limited source of electrical energy available at the time. Current was produced by galvanic cells, which prevented the use of such "machines". They could not establish themselves against the steam engine or the many types of gas or petrol driven engines.

An important step was made in 1831. Michael Faraday discovered electromagnetic induction. This effect was immediately put to use in generators. In 1866, Werner von Siemens invented the dynamo. This direct current generator uses the magnetic remanence of the magnetic poles to initially produce a small induced current. This induced current is then used to produce an excitation field, which in turn brings the generator up to full power. Further development of these generators has given us the modern day motor.

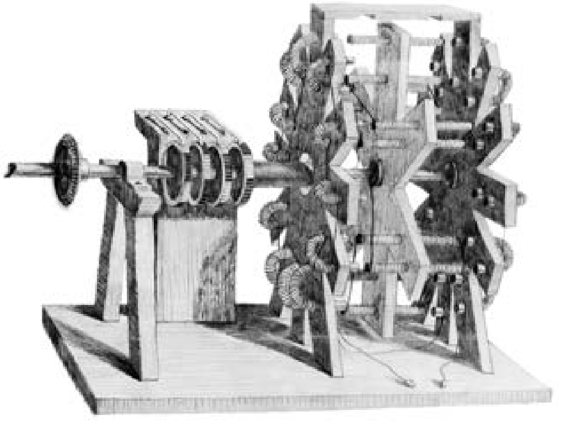

Figure 1.2 Electric motor by Moritz Hermann Jacobi, 1818.
Photograph: Deutsches Museum, Munich

Electrical power transmission 1875 to 1891

At the end of the 19th century, a central problem was supplying energy in the small quantities required for machines in light industries. Steam engines were costly to maintain and for safety reasons could not be used everywhere. Gas powered motors were therefore in widespread use. Competition came from dynamo machines, which had been continuously developed and improved. The arrangement consisted of two, electrically connected dynamo machines. One machine was used as a generator, the other as a motor. In this way, the electrical energy required could be generated at one location, transmitted over a longer distance and then, at the location where it was required, be converted back into mechanical energy. Electrical energy replaced mechanical energy as the transmission medium. The main applications were electric locomotives and street cars but also machine drives, e.g. for weaving machines, were realised.

In 1887, the term "electric motor" appeared for the first time in a sales catalogue. In 1891 the advantages of the electric motor over a steam engine and gas motor were described as being:

- they do not need a fixed foundation, can be mounted in any position, require little space, and can be used in domestic quarters
- they can be run at relatively high speeds, the speed and direction of running can be altered, they have a favourable efficiency and are easy to operate.

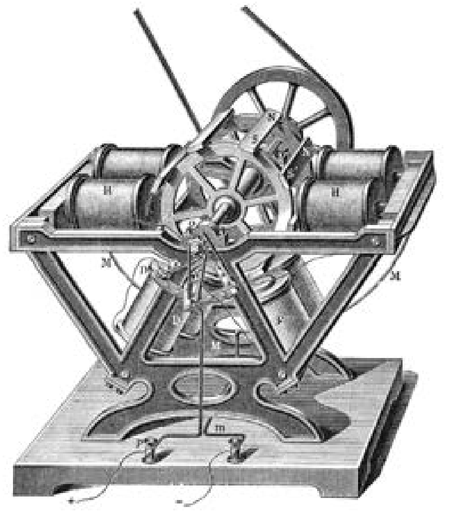

Figure 1.3 Froment's electromagnetic "mouse mill" motor
(from Meyers Konversations-Lexikon 1886)
Photograph: Deutsches Museum, Munich

In 1889, Michael von Dolivo-Dobrowolski invented the three-phase squirrel-cage induction motor. It was he who coined the term three-phase electricity. Additionally, in 1891 he realised the first three-phase power transmission network, from Lauffen am Neckar to Frankfurt am Main, a distance of 175 km.

Electrical drives in commerce and industry 1891 to 1920

At the International Electrotechnical Exhibition of 1891 in Frankfurt am Main, a complete system consisting of generators, transformers, transmission cables, and motors was shown for the very first time. This was the foundation for the introduction of electrical supply networks and electrical drives for both industrial and commercial applications on a

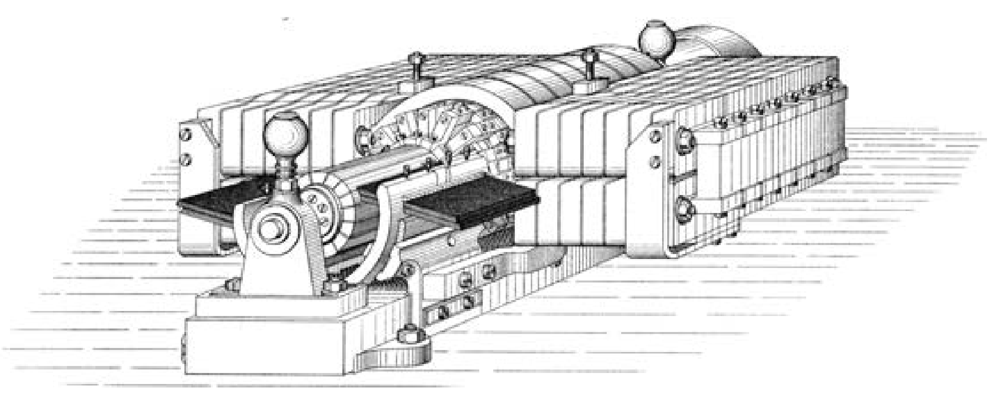

Figure 1.4 Dynamo Siemens & Halske, 1877 supplied for the Oker iron works.
Photograph: Deutsches Museum, Munich

wide scale. Electrical motors were continuously improved with regard to their technical data and their starting characteristics. With the use of resistor networks and the Ward Leonard set (a converter for altering the voltage and frequency), controllable electrical drives became available. This led to the gradual replacement of steam engines and transmission systems in workshops. The machine design could now be optimised to the needs of the manufacturing process and was no longer subordinate to the supply of energy via transmission shafts.

Electrical drives proliferate 1920 to 1950

From around 1920 onwards, electrical drives spread in to all areas of industry, farming, trade crafts, transportation, and into households. Typical drive solutions consisted of DC or AC motors, which depending on the application, were complemented with a controller for adjusting the speed. The number of electrical drives increased significantly. Electrical motors themselves developed in two directions: to integrated solutions within the driven machine, and to standardised mass products. The asynchronous induction motor became the most widely used type in industrial applications. In addition to contactor controls, the first controllers, based on mercury-vapour rectifiers, were used for variable speed applications. Power electronics had found their way into electrical drives.

Converter drives 1950 to 1970

The development of power semiconductors was the beginning of the end for the mercury-vapour rectifier. In parallel, controllers based on analogue electronic components were developed, which supported the spread of variable-speed drives. The simple controllability of DC drives led to their resurgence.

Drives with microprocessor since 1970

The introduction of the microprocessor led to a burst of development in electrical drives. Analogue controllers were replaced by digital ones. Their performance improved continuously, enabling more and more complex functions to be implemented. The development of the “field-oriented control” method by Blaschke in 1971, and its subsequent implementation in a processor-controlled digital drive, enabled AC motors to be controlled with the same control performance as a DC motor.

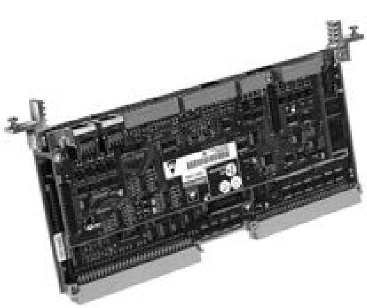

Figure 1.5 Digital control board of a DC drive

Figure 1.6 High power IGBT (Insulated Gate Bipolar Transistor) as used in a frequency converter

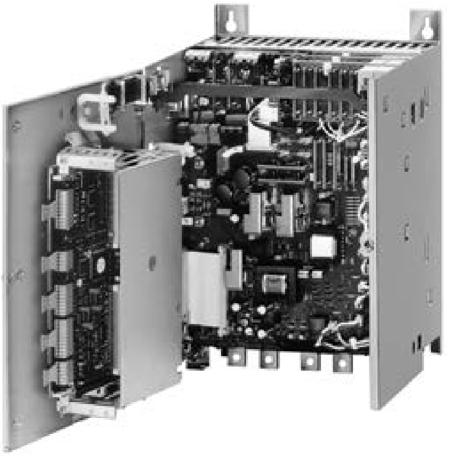

Figure 1.7 Modern digital DC drive converter

The availability of increasingly more powerful microprocessors enabled the integration of functions originally foreign to the drive into the controller. The boundaries between electrical drives and automation devices have become less clearly defined. Drive systems, which consist of electronically-coordinated low-power servo drives, are more and more replacing centralised drives with mechanical gearboxes and main line shafts.

1.2 Design of modern electrical drives

The mechanical energy supplied by the electrical drive is used to control the process variables in the driven machine. The mechanical energy must be adjusted or switched on and off to the process needs. For this reason, a modern electrical drive consists not only of an electrical motor but also a host of additional components (see Figure 1.8).

Electric motor

The heart of every electrical drive is its electric motor. It acts as an energy transformer, converting the electrical energy supplied to mechanical energy. In generating operation, e.g. when braking, the energy flow is in the opposite direction: mechanical energy is then converted back into electrical energy.

Motor encoder

A motor-mounted encoder (motor encoder) determines actual quantities such as rotary speed, speed, and position and makes these available to the signal electronics.

Brake

A brake assists the controller in braking the motor and prevents the motor from moving when the controller is switched off. Particularly when handling suspended loads, e.g. robotic arms, elevators, and hoists, the brake holds the mechanical system tight even when the drive is inactive.

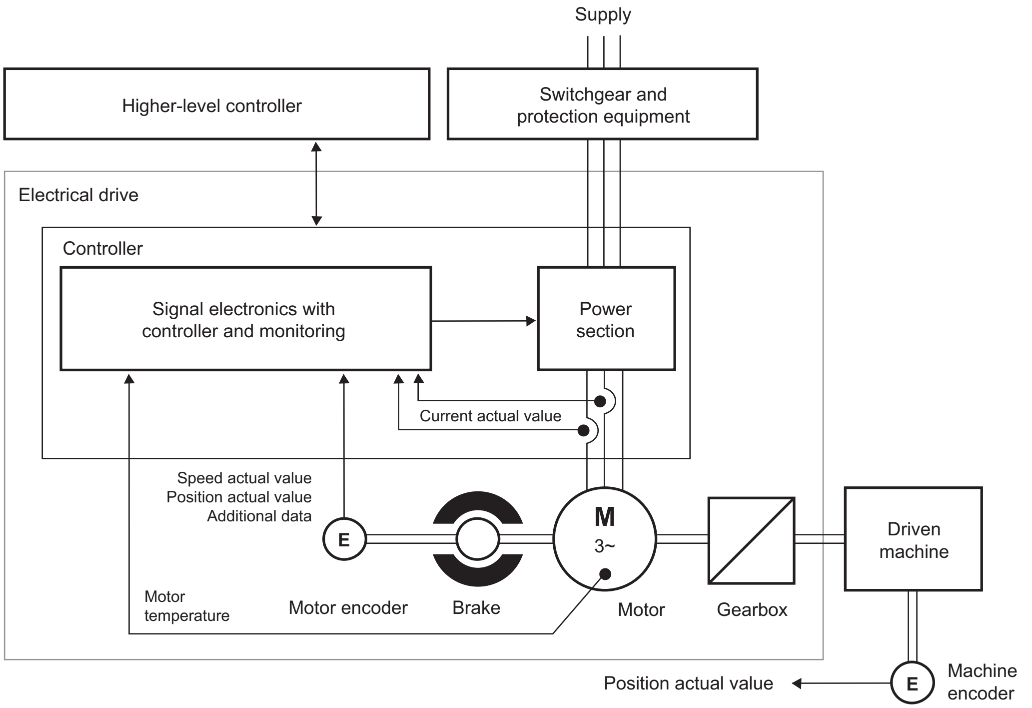

Figure 1.8 Functional blocks of a modern electrical drive

Gearbox

A gearbox is a mechanical transformer. It matches the mechanical quantities supplied by the motor such as speed and torque to those required by the driven machine.

A further task is to convert the rotary motion of a motor into a linear movement where necessary.

Switchgear and protection equipment

Switchgear and protection equipment disconnect the electrical drive from the supply when necessary and protect the drive and supply cables from overload. Overloading can be caused by the driven machine itself or be the result of a fault in the drive.

Controller

A controller consists of a power section and signal electronics:

- the *power section* "portions" the electrical energy to the motor and therefore influences the mechanical energy delivered by the motor. The power section of modern electrical drives is based on power semiconductors. These act as electrical switches, switching the flow of electrical energy to the motor on and off. Integrated measurement systems measure the electrical currents and voltages and make these available to the signal electronics.
- the *signal electronics* is the "brain" of an electrical drive. It determines the control signals for the power section so that the desired power or movement is delivered at the motor shaft. To enable this,

the signal electronics has different control functions. The required electrical quantity actual values are supplied to the signal electronics by the power section, whereas the mechanical quantity actual values such as rotary speed and position are supplied by the motor encoder. The setpoint values are provided to the signal electronics by a higher-level controller, to which the actual values are also communicated. In addition to the necessary control functions, the signal electronics also takes care of protection functions and prevents impermissible overloading of both the power section and the motor.

1.3 Classification of electrical drives

Electrical drives are very diverse and are available in many different designs. It is therefore relatively difficult to classify them and can only be done so by selecting certain criteria, i.e. from a particular perspective. The combination and exact selection of these criteria then give a wide-range of possible drive solutions.

In the following the electrical drives are classified based on the following criteria:

- adjustability of the speed
- motor type and drive controller
- technical data.

1.3.1 Speed variability

The requirements of an application on speed variability are often decisive for the selection of the drive solution. Depending on their speed variability, drives can be roughly divided into three categories:

- fixed-speed drives
- variable-speed drives
- servo drives.

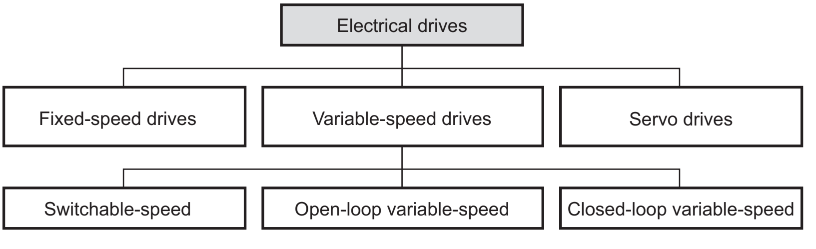

Figure 1.9 Classification of electrical drives by their speed variability

Fixed-speed drives

Fixed-speed drives are operated at a single, constant speed. They possess only the equipment necessary for switching on and off, as well as for protecting against overload. It is not possible to vary the speed of the drive, which means that depending on the load the speed may fluctuate. Typical applications for fixed-speed drives are fans and pumps which are operated with an asynchronous motor direct-on-line.

Variable-speed drives

The speed of variable-speed drives is adjustable and the drives can be operated at at least two different speeds. In addition to an electric motor, these drives have a controller which is responsible for adjusting the speed. Depending on the application, the controller is accordingly complex and allows for different speed-ranges and accuracy.

- *Switchable-speed drives* allow operation at at least two different speeds. Example applications are switchable-speed fans and pumps or traversing drives with forward and reverse operation. Asynchronous motors together with the necessary contactor controller are typically used.
- *Open-loop variable-speed drives* have a continuously variable speed. However, there is no feedback of the actual speed, meaning that, depending on the drive type, there may load dependent deviations from the speed setpoint. A controller with an electronic power section is necessary for the speed control. Examples of this type of drive are asynchronous motors with frequency controllers and V/f control.
- *Closed-loop variable-speed drives* also have a continuously variable speed but, in addition, measure the actual speed of the motor. In this way, deviations in the speed from the speed setpoint can be recognised and corrected. To enable this, it is necessary to have a controller with the appropriate control algorithms. A very widespread implementation of the closed-loop variable-speed drive is the asynchronous motor with frequency controller and vector control.

Figure 1.10 Frequency converters and asynchronous motors for variable-speed drives

Servo drives

Servo drives are optimised to realise changes in speed very fast and precise. They are therefore well suited for complex motion tasks which are characterised by continuously changing speeds. Servo drives are used in all areas of machine building and are frequently realised using synchronous motor and servo controllers.

Figure 1.11 Controllers and motors for servo drives

Operating quadrants

Closely related to the speed adjustability is the ability of a drive to change its direction as well as to return energy to the supply system. These drive characteristics can be represented in a speed-torque diagram. Depending on the sign (plus or minus) of the speed and the torque, four quadrants can be defined (see Figure 1.12). In the two motoring (driving) quadrants both speed and torque have the same sign. In the generating (braking) quadrants the signs of the speed and torque are opposite.

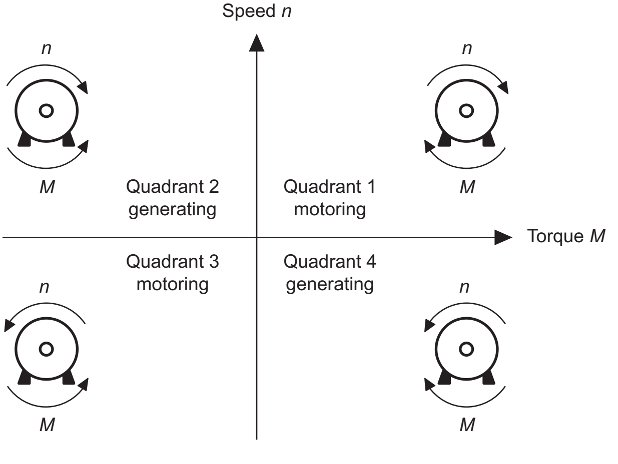

Figure 1.12 Classification of electrical drives by their operating quadrants

Depending on the design of the controller, the electrical drive operates in the first quadrant only, e.g. a pump, or in all four quadrants, e.g. a hoist.

1.3.2 Motor and controller types

Over the course of time, different types of motor have established themselves, each type with strengths and weaknesses, as well as a preferential power range. For this reason, and coupled together with the very long life of the motors themselves, almost all motor types can still be found in use today. Taking the variety of controllers available additionally into account, results in a wide spectrum of drives. Figure 1.13 shows a classification of the basic motor types together with their possible controllers.

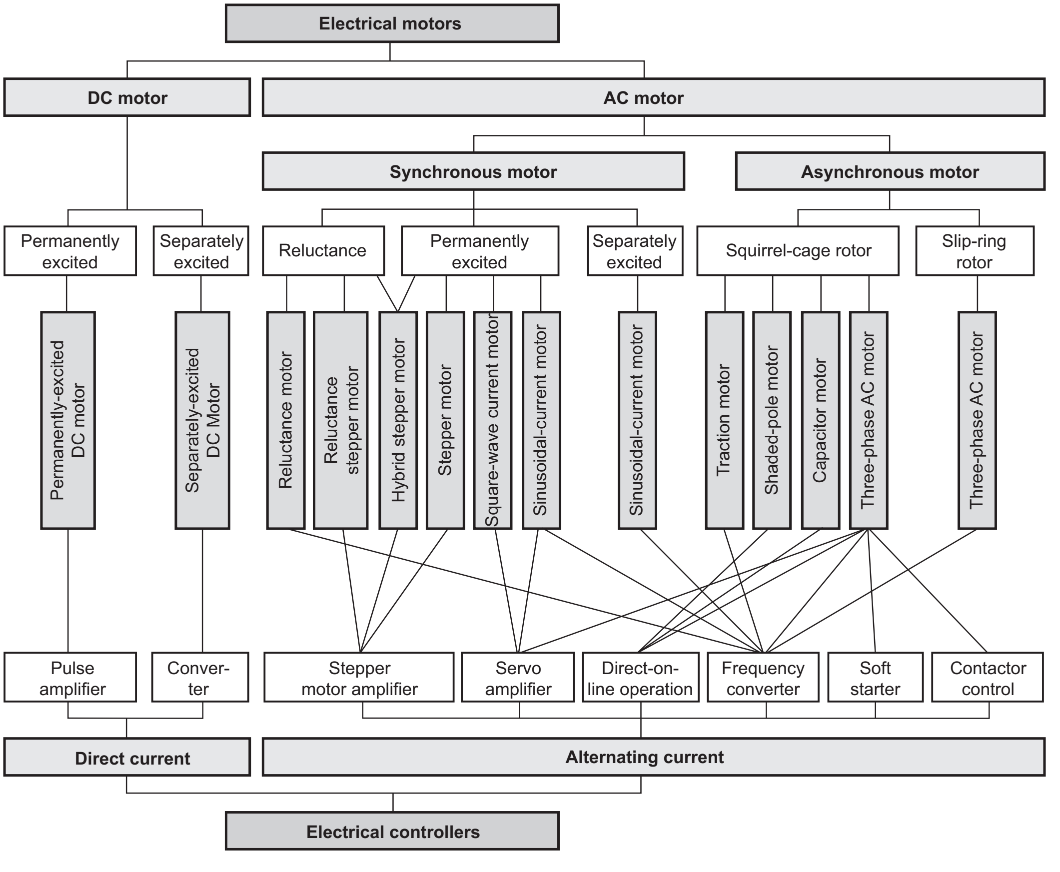

Figure 1.13 Classification of electrical drives by motor and controller

According to the motor current, drives are divided into DC drives and AC drives (single-phase and three-phase).

- *DC drives* use a DC motor. In the lower power range the magnetic field is produced by permanent magnets, in the higher power range with the help of a separate excitation winding. For servo applications highly dynamic pulse-controllers are used, whereas for variable-speed drives converters are used as the controller.
- *AC drives* use motors which are operated from a single-phase or poly-phase AC current. The frequency of the motor current has a significant influence on the motor speed. Synchronous motors follow the frequency of the supply current exactly, whereas in the case of asynchronous motors there is a difference between the frequency of the motor current and the rotational frequency.

Drives with synchronous motors generally have a controller. Asynchronous motors can be operated direct-on-line as well as together with a controller. The choice of the controller depends on the required speed range as well as the required accuracy.

1.3.3 Technical data

Motor data

The technical data are the primary selection criteria for electrical drives. Of central importance are the mechanical and electrical characteristics of the motor. The most important technical data are recorded on the rating plate (see Figure 1.14).

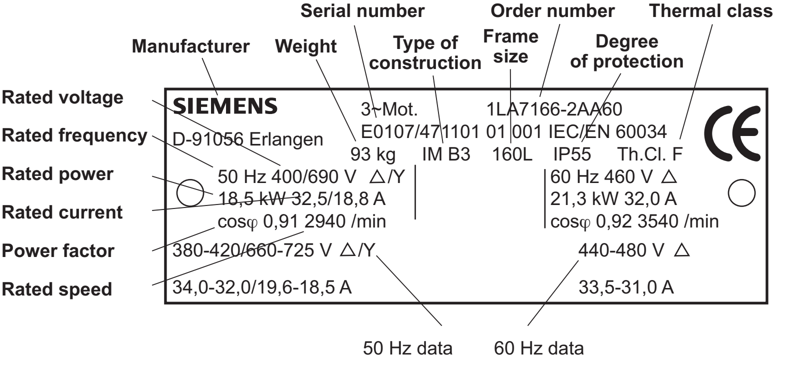

Figure 1.14 Example of a rating plate of an asynchronous motor

Rated data, motor

Of particular significance are the rated data. They specify the motor at its rated operating point; they can therefore be used to compare different motors with each other. Rated data are also known as nominal data.

- *Motor type:* declares whether the motor is a DC, single-phase AC or three-phase AC motor.

- *Rated voltage:* voltage at, or voltage range within which, the motor can be operated continuously. Overvoltages within a certain range are permissible for a short period.
- *Rated current:* current with which the motor can be operated continuously without leading to thermal overloading. Overcurrents within a certain range are permissible for a short period.
- *Rated power:* mechanical power which the motor delivers at its rated operating point. The electrical power consumed can be calculated from the given electrical data. If both the electrical and mechanical data are known, then the efficiency of the motor can be calculated.
- *Power factor:* the power factor enables the active power consumed at the rated operating point for single-phase and three-phase AC motors to be calculated.
- *Rated frequency:* frequency of the supply voltage for single-phase and three-phase AC motors. In the case of asynchronous motors, the rated frequency is usually the same as the line supply frequency, which for industrial networks in Europe is 50 Hz.
- *Rated speed:* speed of the motor at the rated operating point.
- *Rated torque:* torque which the motor delivers when operating with the rated current. This value is of particular importance when selecting a servo motor.

Rated data, controller

Once a motor has been selected based on its rated data, a suitable controller can be found. The controller is specified by its electrical data:

- *rated voltage:* voltage at, or voltage range within which, the controller can be operated. In addition to the voltage, the line supply configuration (single-phase, three-phase, earthing concept) is of importance when selecting the controller.
- *rated current:* output current which the controller can deliver continuously. Many controllers allow overcurrents for a short period, e.g. for accelerating.
- *pulse frequency:* frequency with which the frequency controller and servo controller switches the motor voltage. The higher the frequency, the more dynamic and quieter the drive is.

Mechanical design motor data

In addition to the motor rated data, a range of constructive data is required. They serve to match the motor to the driven machine and to its environment.

- *Type of construction:* describes the permissible direction of mounting and mechanical installation of the motor. The types of construction are described in international standards and are classified as: IM yzz (International Mounting) according to Table 1.1.
- *Frame size (shaft height):* the distance in millimetres between the centre of the motor shaft and the outer edge of the motor.

Table 1.1 Examples of motor mechanical design classification

IM	y: Shaft direction	zz: Mounting method
	B: horizontal V: vertical	specified by either one or two digits
e.g. IM B3	horizontal	foot mounting
e.g. IM B5	horizontal	flange mounting

- *Thermal class:* defines the maximum permissible motor temperature. Exceeding this temperature may lead to premature ageing of the winding insulation and therefore to early failure. The thermal classes are defined in international standards and are recorded using a single capital letter. Example: Thermal class F denotes an average permissible motor temperature of 140 °C.
- *Degree of protection:* classifies the degree of protection of the motor provided against the ingress of solid objects. The degrees of protection are documented in international standards and are classified as follows:
  IPxy (International Protection) with

Table 1.2 Example of motor degree of protection classification

IP	x: degree of protection against contact with body parts and ingress of solid foreign objects	y: degree of protection against ingress of liquids
e.g. IP54	**5:** ingress of dust is not entirely prevented but it must not enter in sufficient quantity to interfere with satisfactory operation, complete protection against contact with tools or similar objects	**4:** protection against water splashing from any direction

In addition to the data named, there are numerous additional characteristics used for specifying a motor. These are described in detail in the manufacturer's catalogue.

Figure 1.15
Asynchronous motor with IM B3 type of construction and IP55 degree of protection

System data

The system data describe the characteristics of open-loop and closed-loop controlled drives comprising of motor, encoder, and controller. They are usually not published by the manufacturer and must be requested.

- *Speed range:* range, in relation to the rated speed, within which the speed can be adjusted with a specified accuracy.
- *Speed and torque accuracy:* deviation between the setpoint and actual value in relation to the rated value.

Servo drives have additional relevant system data which are described in more detail in later chapters.

2 Mechanical principles

Electrical drives provide the machine to be driven with mechanical energy. To describe the flow of mechanical energy and the associated movement, the physical quantities and laws of translational and rotational motion are used. They are summarised in the following table.

Table 2.1 Quantities and equations of translational motion

Quantity	Unit symbol	Definition	Unit	Explanation
distance	s		m	
speed	v	$v = \frac{ds}{dt}$	m/s	The speed v is the change in distance ds per unit time dt.
acceleration	a	$a = \frac{dv}{dt}$	m/s²	The acceleration a is the change in speed dv per unit time dt.
mass	m		kg	
force	F	$F = m \cdot a$	N (kg·m/s², Newton)	
mechanical power	P	$P = F \cdot v$	W (Watt)	The instantaneous power P is the product of the actual force F and the actual speed v.
efficiency	η	$\eta = \frac{P_{output}}{P_{input}}$		The efficiency η is the ratio of the output power to input power.

Table 2.2 Quantities and equations of rotational motion

Quantity	Unit symbol	Definition	Unit	Explanation
angle	ϕ			The value is quoted in radians. An angle of 2π is equivalent to 360°.
angular speed	ω	$\omega = \frac{d\phi}{dt}$	1/s	The angular speed ω is the change in angle dϕ per unit time dt.
angular acceleration	α	$\alpha = \frac{d\omega}{dt}$	1/s²	The angular acceleration is the change in angular speed dω per unit time dt.
torque	M	$M = F \cdot r$	Nm	The torque M describes the effect of a force which acts on a lever of length r.

Table 2.2 Quantities and equations of rotational motion *(cont.)*

Quantity	Unit symbol	Definition	Unit	Explanation
moment of inertia	J	$M = J \cdot \frac{d\omega}{dt}$	kg m^2	The torque M necessary to accelerate is the product of the moment of inertia J and the angular acceleration $d\omega/dt$.
mechanical power	P	$P = M \cdot \omega$	W (Watt)	The instantaneous power P is the product of the actual torque M and the actual angular speed ω.
efficiency	η	$\eta = \frac{P_{output}}{P_{input}}$		The efficiency η is the ratio of the power output to the power input.
frequency	f	$f = \frac{\omega}{2\pi}$	Hz (Hertz)	The frequency f describes the number of oscillations per unit time.
period	T	$T = \frac{1}{f}$	s	The period T is the reciprocal value of the frequency f.
speed	n	$n = f \cdot 60$ (in Hz)	1/min	The speed n corresponds to the frequency f when expressed in 1/min.
transmission ratio, gear ratio	i	$i = \frac{n_{Drive\ side}}{n_{Driven\ side}}$		

3 Electrical principles

3.1 Fields in electrical engineering

Electrical drives utilise the effects of fields. A field defines a space in which forces act upon objects or particles. A field pattern is used to visually represent the action of the force. The action of the force is tangential to the field lines. The closer the field lines are together, the greater the action of the force.

In electrical engineering, electric fields and magnetic fields are of significance (other fields that exist are for example gravity fields and sound fields). Both fields are utilised in electrical drives.

Electric field

An electric field describes a space in which forces act upon charged electrical particles (see Figure 3.1). The forces are exerted by the charged particles themselves. Charged particles can either be positively or negatively charged. The following applies:

- similarly charged particles repel each other
- oppositely charged particles attract each other.

If charged particles are introduced into an electric field, they begin to move, resulting in an electric current. The *electric current* describes the number of charged particles which move from point a to point b in a defined time. Depending on the direction of movement of the charged particles, energy is either set free or absorbed.

The *electric voltage* describes the electric field in total, and can be interpreted as a measure of the difference in energy of a charged particle at different points in the electric field in relation to its charge.

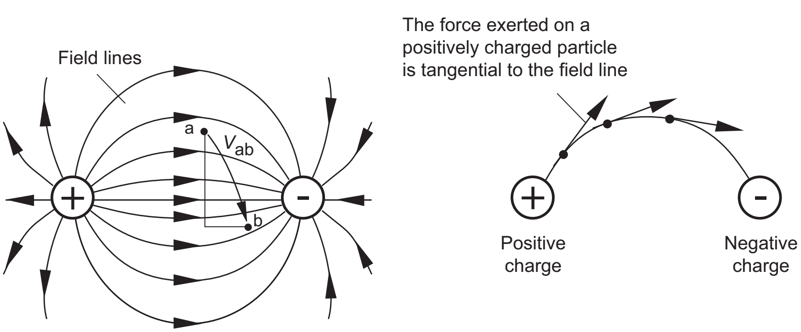

Figure 3.1 An electric field

Magnetic field

A magnetic field describes a space in which forces act upon magnetic bodies (see Figure 3.2). This results in, for example, a magnetic needle aligning itself in a magnetic field.

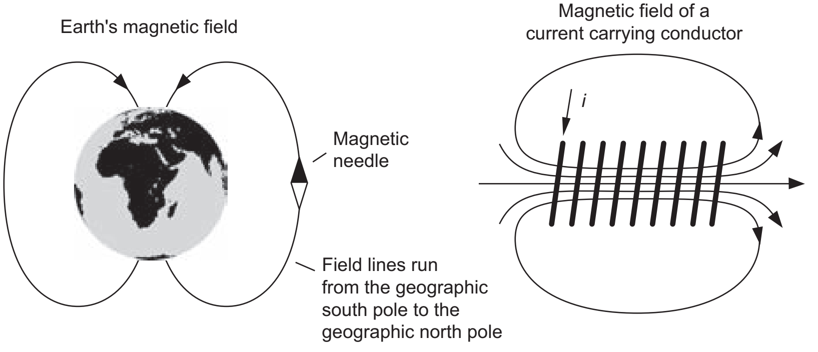

Figure 3.2 A magnetic field

A magnetic field can be produced in two different ways:

- in the case of *natural magnetism* the magnetic field is a property of the material. Certain materials, e.g. "hard" magnetic iron, are surrounded by a magnetic field.
- in the case of an *artificial magnetic field* the magnetic field is created by the movement of electric charge carriers (current flow), e.g. in an electrical conductor. All current carrying conductors are surrounded by such a magnetic field.

Both effects for creating a magnetic field are used in electric motors.

The magnetic fields in motors are channelled in magnetic circuits made from iron. Air clearances and gaps are kept as small as possible as they weaken the magnetic field. Iron amplifies the magnetic field. Magnetically, iron can be classified as being magnetically "soft" or "hard" (see Figure 3.3):

- *"soft" magnetic iron* is only itself magnetic when it is within an external magnetic field. If the magnetic field is removed, e.g. by switching off the magnetic-field producing current, then the iron is also no longer magnetic. "Soft" magnetic iron has a very small hysteresis loop area and therefore low magnetizing and demagnetizing losses. For this reason, motor components subject to changing magnetic fields must be constructed from "soft" magnetic iron.
- *"hard" magnetic iron* is characterised by a remanent (retentive) magnetic field. It is suitable for use in permanent magnets. However "hard" magnetic iron is seldom used for the permanent magnets in motors as other, magnetically stronger materials such as samarium-cobalt (SmCo) or neodymium-iron-boron (NdFeB), are available.