1

Introduction to electrical machine drives control

Few technologies are more important to our collective quality of life than electrical drive technology. One could say that electric motors drive and electric generators power the world. Further, power electronics offers an indefatigable tool for accurate power conversion. And it seems the importance of the technology is poised to rise to even greater heights in the course of the next few decades as more reliable, more cost effective, and more flexible electrical drive systems become available.

For more than a century, electrical machine drives have been powering production processes for numerous industries. Applications include pumping, ventilation, compression, milling, crushing, grinding, conveying, and transporting. In modern robot-dependent manufacturing systems, electrical drives are responsible for precise position control of various robot arms and end effectors.

Concerns about air quality in cities and the increasing demand for improvements in energy efficiency favour using even more electric or hybrid vehicles for transportation needs. The current rate of change toward even more electromobility is limited only by today's high price of electric storage technology. The electrical drives themselves, that is, the motors and converters, are more than sufficient to serve as a replacement for the existing internal combustion engines in cars and buses.

Today, more than 50% of the world population lives in urban areas, and that percentage is growing. This growth in population powers increasing demand for more and better methods of moving people, materials, and things. Electrical machine drives are becoming an increasingly essential element of these transportation applications. Globalization, the accelerating process of international integration, puts added demand on sea and air transport, and ships and even aircraft are relying more and more on the most up-to-date electrical drive systems.

Electrical Machine Drives Control: An Introduction, First Edition. Juha Pyrhönen, Valéria Hrabovcová
and R. Scott Semken.

In addition, the average age of the world population is advancing at a rate unparalleled in human history. By 2050, the elderly will account for 16% of the global population. Caring for these 1.5 billion senior citizens over the age of 65 will strain the world's existing healthcare infrastructure. Fortunately, intelligent machinery has the potential to address the needs of the ageing population and to ease this demographic challenge. As the sinew of intelligent machinery, the increasing importance of electrical machines drives again seems to be clear.

Climate change is also bringing about ever more troubling environmental challenges. Permafrost in Siberia is melting and releasing methane into the atmosphere, there are stronger and increasingly damaging storms, and many drought areas are experiencing unprecedented levels of dryness. The burning of carbon-based fossil fuels to produce both electrical and motive power has been identified as a major contributor to climate change, and moving toward electrical power production technologies that do not burn fuels is a possible solution. Electrical generator drives are essential components of several of the more climate-friendly power production options currently available such as hydro, wind, and geothermal. Moreover, electric vehicles, a green alternative to fuel-burning cars, buses, and trucks, also rely on electrical motor drives.

At present, electric motors are the world's single biggest consumer of electricity, accounting for about 70% of industrial power consumption and nearly 45% of total global electricity consumption. Most in service are polyphase current (AC) induction motors, which are inexpensive and easy to maintain and can be directly connected to an AC power source. However, the majority of these AC induction motors lack flexible speed control, so they are not being used as efficiently as possible. Modern electrical drive technology is beginning to offer more cost-effective solutions with excellent speed control, making it possible to significantly improve efficiencies and minimize power consumption. These developments will encourage the replacement of AC motor systems in existing applications and the implementation of modern electrical drives for any new ones.

1.1 What is an electrical machine drive?

The word *drive* comes from the Anglo-Saxon word *dríf-an*, which was a verb meaning *to urge (an animal or person) to move*. It is used as a noun here that can be defined as *the means for giving motion to a machine or machine part*. Therefore, an *electrical drive* can be defined as an electrical means of imparting motion. When an electrical drive is operated in reverse, it becomes a means of harnessing motion to generate electricity. To be more specific, when an electrical drive is driving, it can be referred to as an *electrical motor drive*. When it is driven, it can be referred to as an *electrical generator drive*.

Depending on the application, electric machines often operate in both motoring and generating modes. And, often, there is no technology difference between an electrical motor drive and an electrical generator drive. For example, the electric drive motor that propels an electric train or automobile—referred to as a traction motor—must run forward and backward and brake in both directions.

Electrical machine drives can be categorized as either noncontrolled or controlled motor or generator drives. Most motor drives working in industrial applications are noncontrolled. Almost exclusively, these are three-phase AC induction motors with direct on line (DOL) or across the line starting. Large-scale power generation mostly uses DOL drives based on synchronous generator drives.

To improve performance and efficiency, many applications are making use of controlled electrical drives. Controlled electrical motor drives are starting to become more popular in cases where the drives are tied into an industrial automation system. Distributed generation is driving demand in electrical power industries for speed-controlled electrical generator drives. In wind power, for example, so-called full power converters are becoming more common where both the generator and the network connection are fully controlled via power electronics.

1.2 Controlled variable speed drives

The primary function of any variable speed drive is to control speed, force production, acceleration, deceleration, and direction of movement, whether it be rotary or linear. Unlike constant speed electric machines, variable speed drives can smoothly change speed to anywhere within their design operating range, and this adjustability makes it possible to optimize production processes for improved product quality, production speed, or safety.

Electrical variable speed drives are offered in a number of basic types, but the two most versatile for general purpose applications, and therefore the most common, are direct current (DC) drives and adjustable frequency AC drives. An electrical variable speed drive typically includes the following three principle elements.

The *high-level controller* enables (a) the operator to start, stop, and change speed via a human-machine interface (HMI) using buttons, switches, and potentiometers or (b) a plant control and set point master computer to send similar commands.

The *drive controller* converts the fixed voltage and frequency of an AC power source into adjustable power output to control the electric drive motor over its range of speeds.

The *drive motor* transforms electrical energy into motor movement. Shaft rotation or linear actuator movement speed varies with power applied by the drive controller.

1.2.1 DC variable speed drives

DC drives are motor speed control systems based on DC motors or generators.

In a traditional rotary DC motor, the rotor (armature) spins inside a magnetic field that is initially produced either electromagnetically or via attached permanent magnets (PMs). The most common electromagnetic approach is to supply the field and armature windings separately. The result is referred to as a separately excited DC motor. If, instead, the no-load magnetic field is produced using PMs, the result is referred to as a PMDC motor. Separately excited and PMDC represent two of the more important and commonly used DC motor types.

In a separately excited and compensated DC motor, speed is directly proportional to the voltage applied to the armature and inversely proportional to motor flux, which is a function of field current. As a result, speed can be controlled via either armature voltage or field current. In a PMDC motor, speed is also directly proportional to the applied voltage. However, since the PMDC magnetic field remains constant, PMDC motor speed cannot be increased beyond the rated speed by reducing armature field current.

DC drive control

The speed and torque of a DC motor are independent. Speed is proportional to the applied voltage, and torque is proportional to the applied current.

As in all drives, power varies in direct proportion to speed. That is, 100% rated power is developed only at 100% rated motor speed with rated torque. Constant power over a specified speed range is needed for some applications. An armature-controlled DC drive can deliver less-than-maximum nearly constant power over a portion of its operating speed range. Because it is a function of speed, the level of power available depends on where in the speed range it is needed. For example, a particular drive might be capable of delivering 50% of its maximum power from 50% to 100% of its rated speed, so if 4 kW was needed over the upper half of the drives speed range, an armature-voltage–controlled drive rated for 8 kW would be required.

In addition to being armature-voltage controllable, the performance of separately excited DC drives can be influenced by changes in field current. Normally, they operate using a constant field excitation, but they can be pushed over their rated speed by reducing field flux beyond the rated speed point. This is called field weakening.

The advantages of the DC drive

Brushed DC motors are more complicated than AC motors and require more maintenance. Their most vulnerable component is the mechanical commutator, which acts as a mechanical inverter in a motor or a mechanical rectifier in a generator. The maximum speed of a DC motor depends on its mechanical endurance, which may be limited because of the commutator and brushes. Some of the disadvantages of the traditional DC motor can be overcome with a brushless DC motor architecture. The brushless DC motor moves the armature to the stator side and uses power-electronic commutation. Its architecture is similar to that of a PM synchronous AC motor.

The primary advantages can be summarized as follows.

- DC drives can be less complex and less expensive for most power ratings.
- DC drives can provide starting and accelerating torques exceeding 400% of rated (Sowmya, 2014).
- DC drives are able to control speed over a wide range (above and below rated speed).
- DC drives can be quick starting, stopping, reversing, and accelerating.
- DC drives offer accurate speed control and a linear speed-torque curve.
- DC drives dominate in sub-kilowatt power applications.
- DC drives are easier to understand for maintenance and operations personnel.

1.2.2 AC variable speed drives

AC drives are machine speed control systems based on AC motors or generators. AC motors typically operate using three-phase AC. Single-phase supplied AC induction motors are also widely used for lighter duty applications. The motors can be rotary or linear. In general, the controller characteristics are the same for either. For clarity, the following discussion focuses on rotary AC motor drives.

A rotary AC motor has a stationary stator and a spinning rotor. The stator is wound with a circular array of conductor coils (the windings) that produces static lines of current and a rotating magnetic field. The rotor carries lines of current that also produce a magnetic field. Both rotate as the rotor spins. The interaction between the rotor or stator currents and the common rotating magnetic field is responsible for the force production (torque) of the motor. Depending on motor type, the rotor currents may be produced via electromagnetic induction or via an active set of rotor windings. In a PM machine, the function of the stator is the same. However, the PM rotor lacks the lines of current and only contributes a spinning magnetic field. In analysis, the PM can be replaced by an equivalent current, if needed. The stator currents and the common rotating magnetic field are responsible for force production in a PM machine.

The two most common AC motor types are induction motors and synchronous motors, each with a number of variations.

The induction motor

An induction motor (also called an asynchronous motor) relies on a slight difference in speed between the rotating magnetic field of the stator and the rotating speed of the rotor to induce current in the rotor's AC windings or integral conductive squirrel cage. This difference in speed is referred to as *slip*.

Single-phase supplied AC induction motors are often two-phase capacitor-run motors. They can exhibit good performance properties for a particular working condition. Because induced coil currents produce a virtual second phase during operation, shaded-pole induction motors act like two-phase motors with their virtual second phase working as a short-circuit winding that produces a rotating field component in the air gap to start the motor. The single-phase motor types are not excellent performers. In general, they are not as efficient as multiple-phase induction motors; however, they are ubiquitous in both industrial and household settings, because of their simple construction, low cost, and reliability and because single-phase voltage sources are readily available. Single-phase frequency converters and small three-phase motors are available if speed-controllable single-phase motor drives are required. Naturally, this should be the trend to enhance energy efficiency.

Three-phase induction motors are the workhorses of industry. The two most common types use either active rotor windings or a rotor squirrel-cage architecture. Because in the first type AC current is transmitted to the active rotor windings via slip rings, it is commonly referred to as a slip-ring induction motor. The second type is referred to as a squirrel-cage induction motor.

Slip-ring induction motors equipped with external rotor resistors have high starting torque, smooth acceleration under heavy loads, adjustable speed, and good running characteristics. Traditionally, they have been used in applications such as lifts, cranes, and conveyors. More recently, their general popularity and market share have dropped off significantly. However, the doubly fed induction generator, a slip-ring machine, remains the most popular generator type for wind turbines. Squirrel-cage induction motors are simpler and rugged in construction. They are relatively inexpensive and require little maintenance. They are the preferred choice for lathes, drilling machines, pumps, and compressors, among other applications.

The synchronous motor

In contrast to the induction motor, a synchronous motor does not rely on slip induction. The magnetic poles of its rotor remain magnetically locked with the rotating air-gap magnetic field, which is synchronous with the frequency of the AC supply current. In a synchronous motor, the rotor poles are produced via an active set of windings or a circular array of PMs.

Synchronous motors are available with power ratings from less than 1 kW to tens of megawatts. Typically, sub-kilowatt synchronous motors are used in applications where a precise constant speed is needed, such as in clocks, timers, and tape players. Above 10 kW, the main benefits of synchronous motors are their high efficiency and an ability to provide power-factor correction. Larger synchronous motors can be found in higher-powered fans and blowers. Three-phase synchronous motors are also being used as traction motors for electric vehicles. The best-known example of synchronous traction motor use in an electric vehicle is France’s high-speed TGV trains (for *Train à Grande Vitesse*, which is French for “high-speed train”). The largest synchronous motor drive is the ABB-supplied 101-MW wind tunnel drive motor owned and operated by the USA National Aeronautics and Space Administration (NASA).

AC drive control

There are various methods used to transform incoming AC power into the adjustable form of input needed to control AC motor speed and torque. Two well-known examples are pulse-width modulation (PWM) and six-step or trapezoidal waveform conversion.

PWM varies the average value of voltage (and current) by rapidly switching (on and off) the voltage input to the motor. The relative duration of the on and off periods, referred to as the duty cycle, determines the amount of voltage supplied. Long on periods and short off periods correspond to high voltage, and short on periods and long off periods correspond to low voltage. Duty cycle is expressed in percentage with 100% being maximum voltage. PWM assumes inductive loads. With inductance, energy can be stored within the magnetic circuit to maintain relatively smooth current in response to the PWM supply.

For an AC drive to operate smoothly in response to PWM, the motor must receive on-off switching pulses that are short relative to the time it takes for the load to respond. The PWM resultant waveform must appear smooth to the load. Typically, AC drive switching frequencies can be from a few to tens of kHz.

Power electronics (switching devices)

To implement the appropriate power conversion method (to vary frequency and voltage of the motor input power supply), both AC induction motors and synchronous motors are increasingly being coupled with power electronics switching systems to produce variable-speed AC drives. For induction motors in variable-torque fan, pump, and compressor applications, the result offers significant and important energy savings opportunities. For large synchronous motors, the result also makes it easier to get the massive rotors moving.

These power electronics can be classified based on the different topologies. By far the most common AC drives are voltage-source inverter (VSI) drives. Other topologies include the current-source inverter (CSI), the load commutated inverter (LCI), and the cycloconverter (CCV).

In a VSI, the DC output of a diode-bridge converter stores energy in a capacitor bus to supply voltage input to an inverter. In place of a diode rectifier, AC conversion can also be accomplished using a more complicated active-switch converter capable of four-quadrant operation and two-directional power flow. Most AC drives are VSI with PWM voltage output. In a CSI, the DC output of an SCR-bridge (silicon controlled rectifier, i.e., thyristor) converter stores energy in a series-reactor connection to supply current input to an inverter. CSIs typically output PWM or a six-step waveform. In an LCI drive, the DC output of an SCR-bridge converter stores energy via a DC-link inductor circuit to supply a second SCR-bridge inverter. LCIs output quasi-sinusoidal six-step current. The CCV is a direct frequency converter approach that transforms an incoming AC waveform of constant frequency and voltage into an outgoing AC waveform of varying frequency and varying voltage.

The advantages of the AC drive

The primary advantages of the speed-controlled AC drive can be summarized as follows.

- AC drives can be smaller and lighter for higher power ratings.
- AC drives can accommodate widely varying loads or extended low-load operation.
- AC drives can operate more easily at higher speeds (over 3000 or 3600 rpm).
- AC drives need less apparent starting power and offer lower-cost electronic motor reversing.
- AC drives offer better speed and torque control.
- AC drives are more common in high power applications.
- AC drives require less maintenance are a better choice when access is limited.

1.3 Electrical machine drive implementation

Figure 1.1 compares typical configurations for a controlled and noncontrolled drive. The shaded areas represent the core electrical drive components. In each case, the primary inputs are power, either electrical or mechanical, and the control signal, which could be speed, torque, or position for the controlled drive or simply an on/off command for the noncontrolled drive. Output is the mechanical power of the output shaft for a motor drive or the generated electricity for a generator drive.

Instrumentation monitors the state of the motor by measuring critical parameters such as rotation speed, electric current, and operating temperature. The measurement signals are transmitted to the controller, which issues control signals to the power electronics based on the input references and transducer signals. Based on signals from the controller, the power

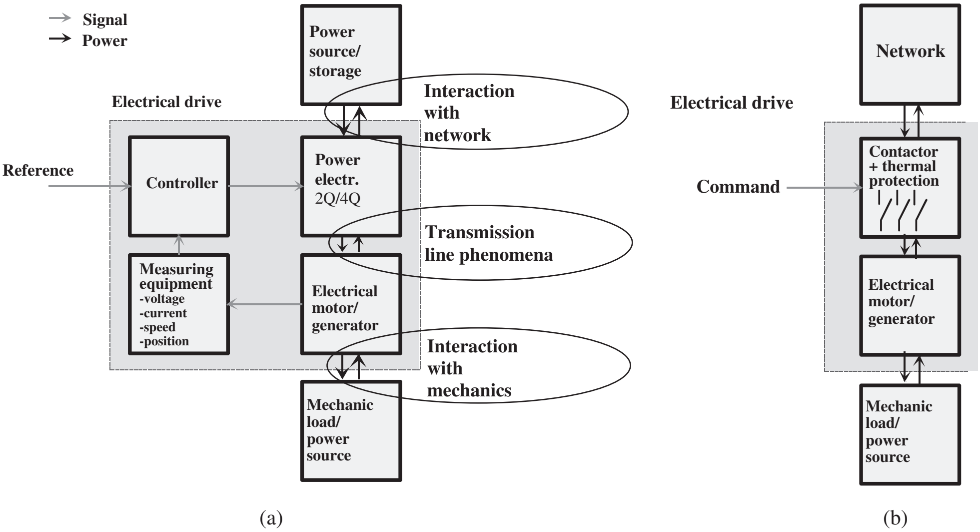

Figure 1.1 Block diagrams illustrating the principles of a controlled and noncontrolled electrical drive where (a) is a drive with a two- or four-quadrant 2Q/4Q power electronic converter and (b) is a direct-on-line drive. The input of an electrical drive consists of electrical or mechanical power and an operational reference. Output is the mechanical or electrical power transmitted either to a mechanical or electric load. In principle, a controlled electrical drive consists of power electronics, an electric motor or generator, monitoring instrumentation, and a controller. A noncontrolled electrical drive consists of a contactor with protective thermal relays and the electric motor or generator. In either case, there are interactions between the drive system and the network, between the power electronic converter and the electric machine (transmission line phenomena), and between the electric machine and the mechanical system.

electronics either converts incoming electrical power to supply motors that produce mechanical power or converts outgoing electrical power to supply a storage system or network in response to incoming mechanical power.

Present-day converters all apply some kind of a modulation technology to convert electrical power from one form to another. The most common is PWM, with which, for example, incoming DC voltage can be converted to a suitable AC voltage to accommodate an AC motor. PWM applies constant voltage in pulses of a given duty cycle (pulses/cycle) and frequency (cycles/second). For electrical drives, PWM depends on the system having a suitable level of inductance to filter the PWM input and to achieve smooth electric current curves despite the chopped voltage.

As implied by the blocks shown in Figure 1.2, the expert in electrical drives should exhibit competence in several technical areas. Obviously, expertise in energy technology, electric machines technology, electrical power network technology, measurement technology, mechanics, control engineering, thermodynamics, and telecommunications technology is required. How the electrical drive system interacts with its mechanical and electrical

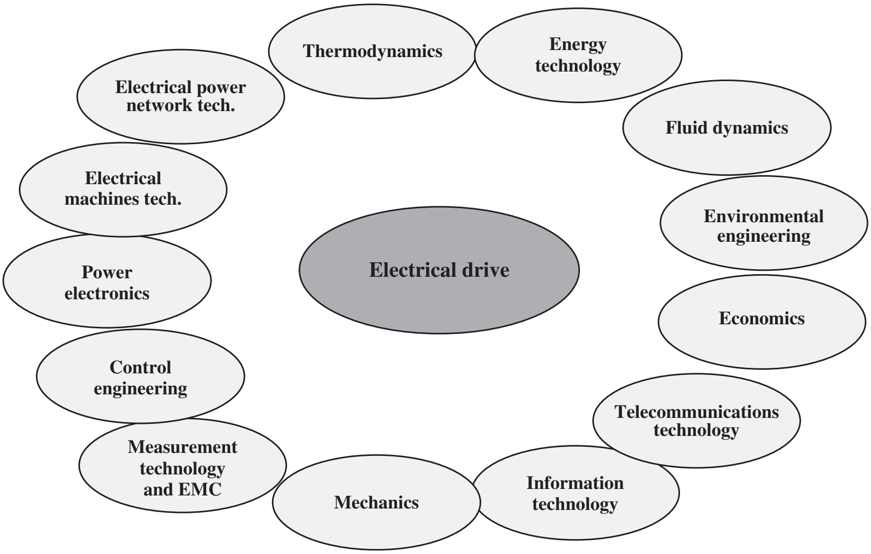

Figure 1.2 Fields of operation of an electrical drives expert. EMC, electromagnetic compatibility.

interfaces also must be understood. Figure 1.2 illustrates the main fields of operation and the areas of expertise of an electrical drives expert.

Telecommunications technology is perhaps not the first thing that comes to mind when considering electrical drives; however, present-day drives such as those used for ship propulsion and wind power are operated and monitored remotely. For example, the condition of electrical drives in ships is monitored in land-based centres via telecommunication protocols utilizing satellites. Similarly, machine systems such as harbour cranes are monitored via the Internet by the manufacturer for maintenance and product development purposes.

1.4 Controlled electrical drives and energy efficiency

The growing use of controlled electrical drives significantly affects overall energy use and energy technology itself. They play an increasingly significant role in the management of global energy consumption. Controlled electrical drives improve energy efficiencies by more accurately controlling process energy flow. The following paragraphs will discuss some of these aspects in more detail.

A great many human activities depend on electromechanical energy conversion. It is particularly important to many industrial processes and for the housing, commerce, and transportation sectors as well. In the early 21st century, global electricity consumption reached 18,500 TWh/a, and current forecasts suggest it will reach 30,000 TWh/a in the near future. Electrical drives will represent 50 to 60% of this total, so it is easy to understand that

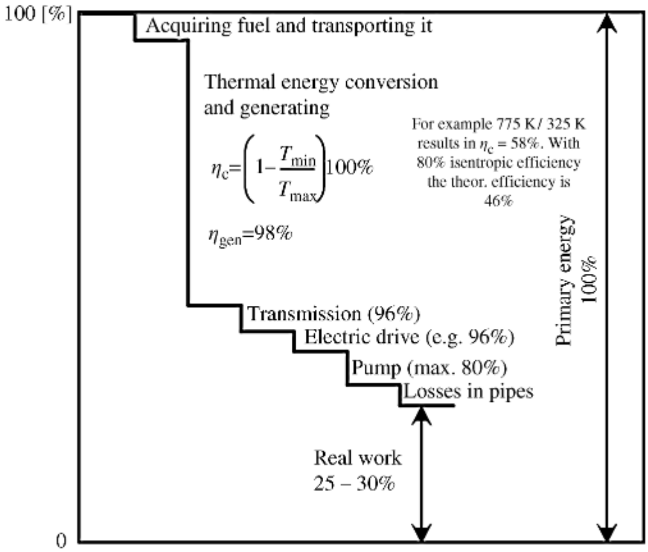

Figure 1.3 Chain of efficiencies in electricity production (from chemical or nuclear energy), transmission, and final use indicating low total efficiency. System performance can be considered acceptable if 25% to 30% of the primary energy can be used to perform useful work; however, actual performance can be significantly lower.

improving electrical drive efficiency is a key factor in reducing consumption and the associated emissions of carbon dioxide (CO_2).

Electricity is still produced mostly by rotary electric machines driven by incoming mechanical power provided by turbines, internal combustion engines, and the like. Electricity production from solar cells and fuel cells is increasing, but so far, generators remain the most important means of energy conversion. Furthermore, the strong future predicted for wind power ensures a continuing important role for rotary electric machines in power generation.

Since most electricity is still produced by burning fossil fuels or by nuclear power, it is important to understand the relationship between primary energy demand and final process efficiency. Figure 1.3 illustrates how the efficiency of each link in a chain of energy conversions leads to a surprising low resultant total efficiency for the electrical energy system of a condensing power plant.

The biggest losses are due to the inherently low efficiencies of thermal cycles producing mechanical work from thermal energy. The maximum theoretical efficiency η_c of a thermomechanical energy conversion is known as the Carnot efficiency and is defined as follows.

$$\eta_C = 1 - \frac{T_{min}}{T_{max}} \tag{1.1}$$

Absolute temperatures $T_{\min}$ and $T_{\max}$ are the minimum and maximum of the thermal cycle. Using a steam power plant as an example, the temperature of the condensed water supplied to the boiler would be $T_{\min}$, and the temperature of the supercharged steam leaving the boiler would be $T_{\max}$. In Figure 1.1, these temperatures are 325 K and 775 K, respectively. The maximum corresponds to the practical upper limit of present-day steam power plants. Cooling the condensed water to the minimum 325 K also is within typical capabilities. For these temperatures, however, Equation (1.1) yields a maximum theoretical efficiency of 58%. When all efficiency-limiting factors are taken into account (e.g., the isentropic efficiency of the turbine (typically 80%) and the power needed to run the power plants components), the actual energy conversion efficiency drops to within the range of 40% to 45%. In combined cycles (e.g., a gas turbine system with waste heat boiler plus steam turbine), it is possible to reach 60% electricity production efficiency, and in places where the heat of the process can be utilized, it is possible to reach 80% total efficiency. Plants that utilize process heat in this way are referred to as combined heat and power (CHP) plants. CHP technology is prevalent and most efficient in northern countries like Finland where water and housing must be heated year round.

The chain of efficiencies illustrated in Figure 1.3 suggests that electricity, which is a highly refined energy carrier, should be reserved for applications that cannot be served using other forms of energy transmission. An electrical drive is one such application. With this in mind, some countries prohibit the use of electricity for direct resistive heating, for example.

A system using a heat pump driven by a PM synchronous motor drive is capable of producing as much as seven units of heat output with just one unit of electricity input (the performance coefficient of the heat pump is typically 3 to 7). Looking again at Figure 1.3 reveals that a heat pump system based on an electrical drive may produce more heat than can be produced by burning fuel directly. If 30% of the original primary energy goes to driving the heat pump and if the performance coefficient is seven, then $0.3 \times 7 = 2.1$, or 210% goes to heat the process. Therefore, if electricity is to be the energy transfer medium used for heating, using an electrical drive to run a heat pump to produce heat energy that is 90 to 210% of the primary energy is better than using direct resistive heating to produce heat energy that is just 30% of the primary energy.

The final process in the chain, pumps and pipelines for the system in Figure 1.3, should have as high efficiency as possible to avoid excessive primary energy consumption. Therefore, the electrical drives expert and the pump specialist should collaborate to select the best possible technology for the final drive. The motor drive, the pump, and the pipelines must work together to achieve optimal final drive efficiencies.

Because electrical drives are more controllable than mechanical or hydraulic systems, their use in many fields of human activity is increasing. Moreover, since electrical drives are typically more energy efficient, they are becoming important from the point of view of energy efficiency.

The latest developments in electrical drives are in mobile equipment such as electric or hybrid vehicles and heavy working machines. Careful integration of electrical drive technologies into mobile equipment systems is resulting in significantly improved energy efficiency, better emission control, and better performance. Hybrid mobile equipment uses electrical motor drives to power the subsystems or the drive wheels. These motor drives are powered by an electrical generator drive, which in turn is powered by an internal combustion engine. Given the nearly constant speed and load required by an electrical generator drive, the internal combustion engine of a hybrid can be sized optimally and designed to operate cleanly at peak efficiency. For example, the efficiency of a modern low emission diesel engine, designed to power the generator of a hybrid excavator (50 to 500 kW), can easily reach an efficiency of 40%.

Electrical power is being produced more efficiently and cleanly, and modern frequency converters are improving the efficiencies of process control as well. Efficient process control can save energy and reduce emissions. To illustrate, one manufacturer of electrical machine drives, ABB, has reported that their installed base accounts for 445 TWh in energy savings; equivalent to the annual production of 56 nuclear reactors or the yearly consumption of more than 110 million households (ABB, 2015). Compared with fossil fuel–generated electricity, this represents a reduction in CO_2 emissions of approximately 336 billion kg, which is the amount emitted in a year by more than 90 million cars. ABB enjoys approximately 20% market share, so real benefits associated with worldwide electrical machine drive usage can be estimated to be roughly 8 EJ in energy savings and 1.7 trillion kg in CO_2 reduction.

1.5 The electrical drive as an element of a controlled industrial process

In industrial processes, effective speed or torque control is necessary to achieve reasonable energy consumption and high quality. This requirement becomes clear if the particular process requirements are analysed. Industrial processes can be divided into two main categories: material transformation and material transportation. In each case, being able to adapt to changing process requirements can lead to improvements in efficiency and quality. The precise control of speed in response to varying load conditions offered by controllable electrical drives provides this ability.

Presently, electrical drives are essential process components in a number of industrial areas, including the chemical industry; fabrication workshops; the plastics industry; the pulp, paper, and printing industries; the food and soft drink industries; mining; metals; and power plants. In addition, many electrical drives are being used for the heating, plumbing, and ventilation of buildings.

All industrial processes require both material and energy. Figure 1.4 shows the energy and material flows for a typical manufacturing process. Energy and material are consumed to output a product. The figure illustrates the energy and material inputs and depicts consumption as energy and material loss outputs. Processing can involve mechanical power, the electromagnetic effect, heating or cooling, chemical reactions, or biological reactions. Mechanical power is applied most effectively via speed-controlled electrical motor drives. With precision speed control available, processes can be developed that produce high-quality results with minimal materials and energy consumption.

Process equipment can be categorized as transport devices, equipment that moves materials from place to place, or processing devices, equipment that modifies the geometries or properties of materials.

Transport devices include various systems to move solid materials and devices for controlled delivery of liquids or gases. Device construction varies depending on

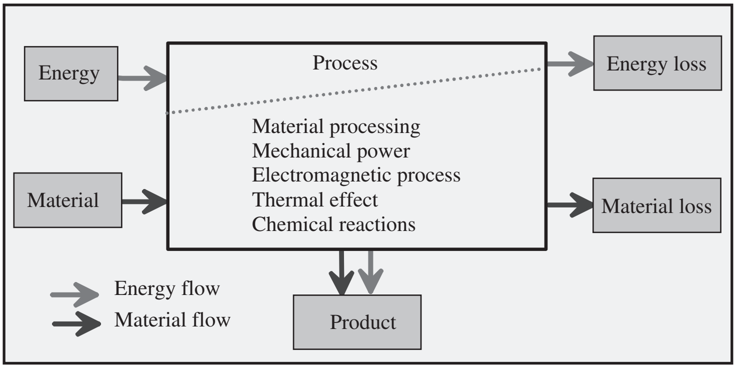

Figure 1.4 Energy and material flows in a typical production process.

material to be transported. Solids such as containers, metals, wood, minerals, or even human beings are moved by hoists, conveyors, lifts, and vehicles. Fluids such as water, oil, or liquid chemicals are transported by pumps through pipes or tubes. Gases are forced by blowers, compressors, or fans through ducts or tubes. A particular application of this kind is air conditioning.

Processing devices carry out a nearly unlimited variety of material modifications. Every electrical process device integrates energy control, an electric motor, mechanical power transmission, and the material modification machinery. An electrical drive provides the first three: energy control, motor, and transmission. It converts the electrical energy fed to the system into the required mechanical energy needed to carry out the processing function of the operating machine. In the most demanding processing tasks, servo drives are needed for precise position control. For example, electrical component placement machines used in circuit card assembly in electronics industry must be controlled precisely to place the components on a circuit card with a high degree of accuracy.

Speed control is an important element of electrical drives. It can be accomplished, for instance, by using a frequency converter to control energy flow or by using mechanical gears as to control power transmission. Frequency converters are popular, because they make it possible to control ordinary noncontrolled electric motors. Newer PM motors, which have greater torque density than induction motors, often can be applied directly without the need for power transmission gearing. Electrical drives are referred to as high-speed drives when the frequency converter feeds the electric motor at a frequency that is notably higher than the line frequency. These high-speed drives are gradually becoming more common.

Table 1.1 reviews some general industrial electrical drive applications and lists some of their more important behavioural characteristics. Table 1.2 lists traditional and more modern methods of achieving different speeds in electrical drives.

Electrical machine drives are the essential workhorses of modern industry. Their successful development and implementation demand expertise from multiple engineering disciplines. When the most appropriate electrical drive is applied correctly to carry out its targeted process function, energy efficiency can be optimized, and the cumulative effects throughout industry can bring substantial environmental benefit.

Table 1.1 Typical industrial (or alike) electrical drive applications

Application	Power [MW]	Typical Speed $[\text{min}^{-1}]$	Starting Torque T_s/T_N	Synchronizing Torque Demand (DOL) $T_{\text{pull-in}}/T_N$	Maximum Load Torque $T_{\max}/T_N$	Moment of Inertia $J_{\text{load}}/J_{\text{motor}}$	Relative Smoothness of Torque
Grinder	2–20	1000–1800	Small $< 20\%$	Small $< 10\%$	Normal 1.5	Normal $J_{\text{load}} \sim j_{\text{motor}}$	Smooth
Chopping Machine	0.1–3	250–500	Small $< 20\%$	Small $< 10\%$	Large 2.5–3	Large $J_{\text{load}} > J_{\text{motor}}$	Large variations
Centrifugal compressor	. . . 20	1000–1800 10,000–100,000	Normal $< 40\%$	Normal $< 40\%$	Normal < 1.5	Fairly large $J_{\text{load}} > J_{\text{motor}}$	Smooth
Reciprocating compressor	. . . 20	150–500	Normal $< 40\%$	Normal $< 40\%$	Fairly large 2	Large $J_{\text{load}} > J_{\text{motor}}$	Periodic variation
Blower	. . . 15	300–1800	Small $< 20\%$	Normal $< 40\%$	Normal 1.5	Large $J_{\text{load}} > J_{\text{motor}}$	Smooth
Centrifugal pump	. . . 10	500–1800	Normal $< 40\%$	Normal $< 40\%$	Normal 1.5	Small $J_{\text{load}} < J_{\text{motor}}$	Smooth
Vacuum pump - Nash - Sulzer	. . . 3 . . . 3	200–400 1000–1800 reduction gear	Small $< 20\%$ Small $< 20\%$	Normal $< 40\%$ Large $\sim 100\%$	Normal 1.5 Normal 1.5	Normal $J_{\text{load}} \sim J_{\text{motor}}$ Fairly large $J_{\text{load}} > J_{\text{motor}}$	Smooth Smooth
Ore or cement mill	. . . 10	150–500	Large $> 100\%$	Large $\sim 100\%$	Fairly large 2	Normal, varies under load	May vary periodically
Position-controlled drives	. . . 0.2	0–6000	High	—	Large	Normal, varies under load	Varies periodically
Propeller	. . . 50	70–300	Small $< 20\%$	Normal $< 40\%$	Normal 1.5	Small $J_{\text{load}} < J_{\text{motor}}$	Smooth
Wind turbine	. . . 10	10–1800	—	—	Normal 1.5	Large $J_{\text{load}} > J_{\text{generator}}$	Smooth
Mobile machine or train traction	0.05–5	1000–6000 Reduction gear	High	—	Normal 1.5	large $J_{\text{load}} > J_{\text{motor}}$	Varies under load
Ship propulsion	1–30	100–	Low	—	Normal	Normal $J_{\text{load}} \sim J_{\text{motor}}$	Smooth

Table 1.2 Traditional and modern speed control means

Control Method	Mechanical Variator	Hydraulic Coupling	Motor Pole Number Switching	Voltage Control	Slip-Ring Machine Cascade	Power-Electronics–Based Control
Power range	0–75 kW	15–12,000 kW	0–5000 kW	0–5 kW	100–10,000 kW	0–100,000 kW
Max speed	4000 min^{-1}	2900 min^{-1}	3000 min^{-1}	3000 min^{-1}	3000 min^{-1}	100,000 min^{-1}
Speed control range [%]	8–100	25–100	25–100 stepped	60–100	50–100	0–100
Speed of torque control	Slow	Slow	Slow	Slow	Fast	Very fast
Speed of speed control	Slow	Slow	Slow	Fairly fast	Fast	Fast

References

ABB. (2015). Energy efficiency. A solution. Retrieved from http://www.slideshare.net/ABBDrivesandControls/energy-efficiency-a-solution-48833156

Sowmya, M., et al. (2014). Closed loop speed regulation of DC motor using phase controlled thyristor converter. *International Journal of Engineering Sciences Research*, 5, article 06368. ISSN: 2230–8504; e-ISSN-2230-8512.