1

Introduction

Gonzalo Abad

1.1 Introduction to the book

This book is mainly focused on the field of what is commonly known as the electric drive. Electric drives are very prevalent in our lives. They are used in many applications or devices throughout the world. Wherever we use a device or element in which a kind of movement is involved, that movement will probably be governed by an electric drive. Examples of such kinds of devices include trains, trams, ships, electric vehicles, elevators, washing machines, air conditioning systems, wind generators, pumps, and rolling mills and so on. Moreover, in order to be effective and efficient, the specific characteristics of the drive designed, for instance, for controlling the drum of a washing machine, will be quite different compared to the electric drive, for example, employed for controlling the speed of rotation of the blades of a specific wind generator. However, in essence, in terms of what we would call basic technology, all these electric drives employed in various applications share a common technological structure, which, in order to be optimized, is adapted to the specific needs of each application.

This book is mainly focused on describing the electric drives employed in four common applications or devices that one can find in real life: railway traction (trains, trams, locomotives, etc.), ships, electric and hybrid vehicles, and last but not least, elevators. As already noted, in all these traction applications, the main movement must be effectively generated and controlled in order to satisfy standards of performance, efficiency, comfort, safety, reliability, etc. For that purpose, electric drives of different characteristics are developed in each application. It is possible to find AC electric drives or DC electric drives, depending on whether the machine they control is AC or DC. In this book, only AC electric drives are treated, since nowadays AC machines have displaced DC machines, owing to their performance capacity, robustness, cost, etc.

Consequently, this book concentrates on AC drives, dividing its contents into eight chapters. The first four chapters deal with the basic technology comprising the electric drive. And the final four chapters look at how this technology is applied to specific applications.

Power Electronics and Electric Drives for Traction Applications, First Edition. Edited by Gonzalo Abad.

To be more specific, the introductory chapter anticipates what the rest of the chapters deal with in detail. It sets out to contextualize, and give a general view of, what are the different parts involved in the design of an electric drive, as well as discussing the most common types of electric drives we find in the subsequently described applications or devices.

Then, in Chapter 2 and 3, the control of electric drives oriented to two electric AC machines is described: induction machines and synchronous machines. These two machines, among the existing ones, are the most employed machines in electric drives for the applications described. After that, in Chapter 4, the control of grid-connected converters is addressed, which is an important part of certain sophisticated electric drives required to regenerate energy to the electric grid. In order to describe this control, some other necessary and connected aspects of the electric drive are also studied in these three chapters, such as models of converters, machines, steady-state performance, and so on.

Thus, it is possible to remark that, in general terms, these four first chapters try, on the one hand, to define and describe the most commonly employed drive topologies and their controls in the applications described in subsequent chapters. These topologies have, over many years of industry use, become successfully established as industry standards, and yet they continue to evolve. While, on the other hand, the first part of the book also tries to provide the necessary mathematics, block diagrams, explanation styles, etc. to facilitate an understanding of the concepts described that will be suitable for engineers or people from the industry and postgraduate students.

The second part of the book describes each mentioned device or application in greater detail. There is one chapter for each application: railway traction, ships, electric and hybrid vehicles, and elevators. To avoid duplication, much of what the last four chapters refer to that is described in the first four chapters is not reproduced. These four chapters, from the point of view of exposition, share a common structure. However, the specific particularities of each application necessitate individual chapters addressing certain aspects that are not treated in all chapters. In general terms, we can highlight the most relevant themes:

- A holistic and global introduction to each application, providing a general view and showing the different practical aspects that determine the further performance requirements of the electric drive;
- The physics and mechanics describing the functioning of the applications. This important aspect helps to explain why the way an electric drive is employed varies from application to application. And having knowledge of the different ways a device functions helps us to understand the stages involved in the design of electric drives, such as the characteristics of control, the volume of the drive, and so on;
- The particularities of each application are translated into different functioning or operation conditions of the electric drive, for example dynamic performances, comfort, repetitive operation cycles, power levels, speed ranges, producing torque characteristics, currents, voltages, volume, space, and so on;
- The development and analysis of global simulation models, based on previously developed physic models and electric drive models, showing the behaviors and performances of each specific application;
- Dimensioning examples of each device, providing ideas and procedures of how the different elements of the drive can be dimensioned in order to fulfill different specifications and requirements;
- The representative manufacturers involved in each product, describing some real examples that can be found in the market;
- The technological evolution experienced by each device, showing the past, present, and future of the whole technology involved; and
- An emphasis on the future trends and challenges for each application. As is mentioned in this chapter, it is possible to say that all the applications under discussion present common general future trends, since they share the same basic electric drive technology. But also, the specificity of each application's needs give rise to other, different trends and challenges for each of the devices.

Thus, finally it must be highlighted that the contents of this book are discussed by various academic and industry experts collaboratively. These contributors have come together to give their perspectives on and solutions to the challenges generated by this continuously evolving technology.

1.2 Traction applications

The necessity for an electric drive arises in such applications, products, or equipment where motion is required. Nowadays, it is possible to find a huge amount of applications surrounding us, where motion is required.

Thus, for instance, something so popular and common nowadays, trains, locomotives, trams, or metros employ a typical traction operation. As illustrated in Fig. 1-1, the traction wagon presents at least one traction bogie, where a special arrangement of mechanical transmissions and electric motors produces the traction effort at the traction wheels. The traction effort at the wheels produces the linear movement of the entire train along the railway. A specifically designed electric drive enables features related to the comfort of the users—such as speed, jerk, and slip—to be controlled.

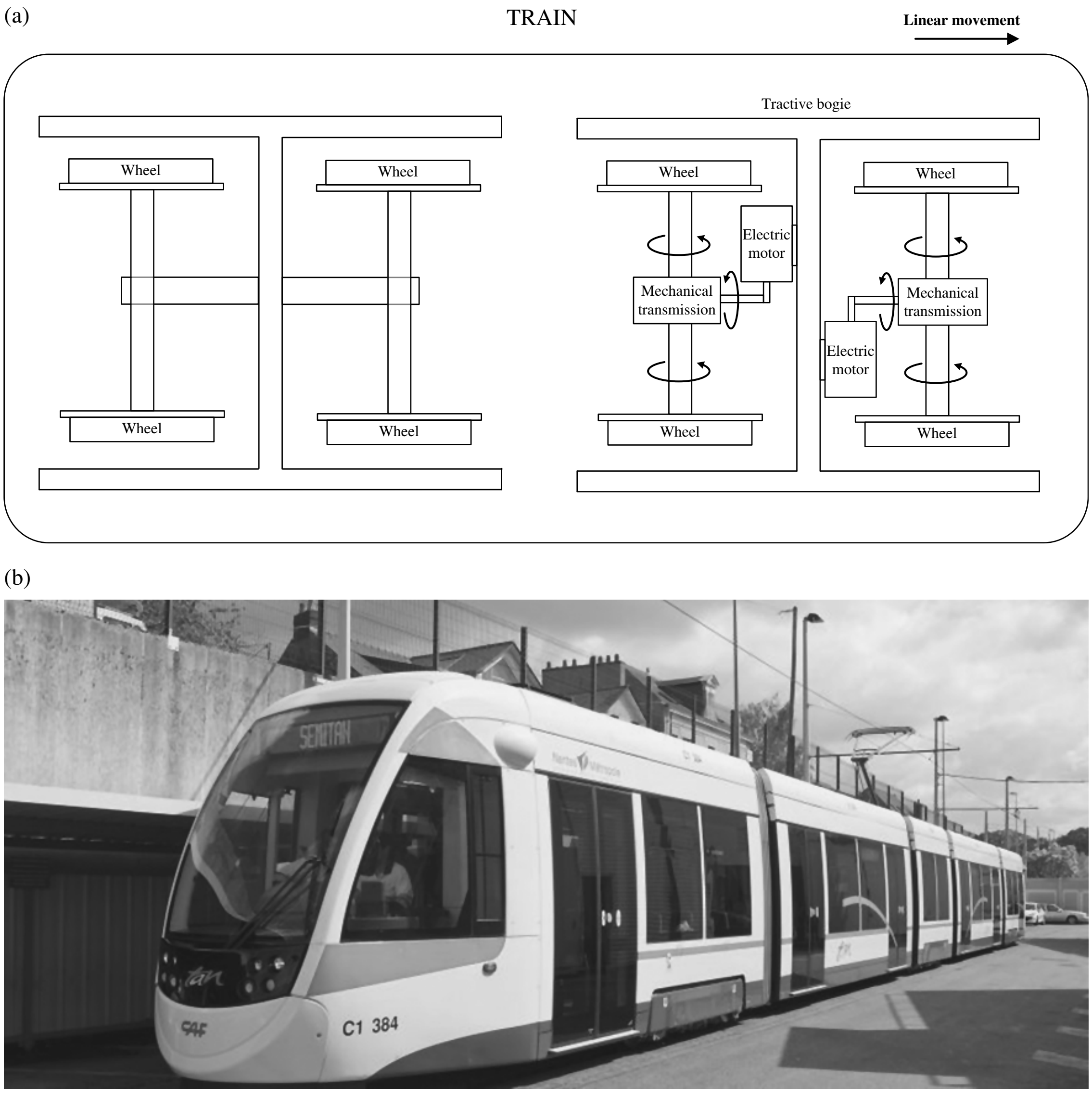


Fig. 1-1 *(a) Schematic representation of the basic movement operation principle of an electric train, (b) Example of a real tram (Source: CAF. Reproduced with permission of CAF)*

Therefore, it can be noticed that, as in most of the applications where movement must be created and controlled, the movement itself is produced by an electric motor. The rotational movement generated at the motor's shaft is then converted to the movement required by the application, which in the train example is the longitudinal movement of the train itself. Additionally, it must be remarked that the movement of the train must be controlled, guaranteeing some basic performances, such as: smooth and comfortable arrivals and accelerations, minimized energy consumption, and reduced noise levels. In order to achieve this, movement is created by what we call an electric drive. The electric drive is discussed in greater detail later in the chapter, but it can be said here, in a simplified way, that it is composed of:

- an electric motor, which generates the rotational movement;
- a power electronic converter, which supplies the electric motor taking the energy from a specific source of energy, enabling the controlled rotational movement of an electric motor;
- a control algorithm, which is in charge of controlling the power electronic converter to obtain the desired performance of the electric motor; and
- an energy source, which in some cases is part of the electric drive and in other cases is considered an external element.

So, too ship applications. In a modern ship, the advance movement is governed by a thruster or a propeller. The thruster creates a rotational movement of the blades, displacing the water surrounding it and producing the advance movement of the ship. Fig. 1-2 gives a schematic representation of the basic movement principle of a

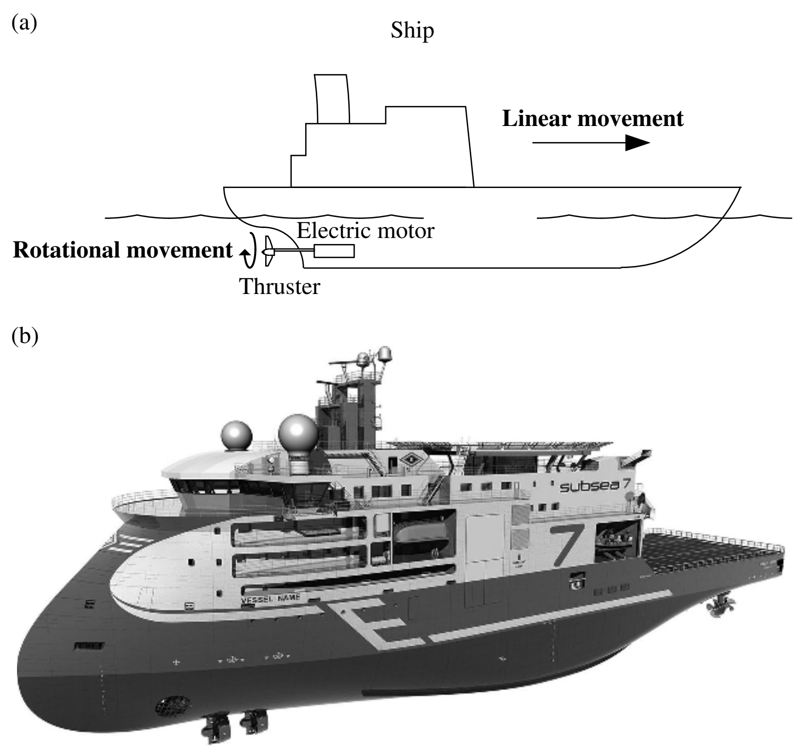


Fig. 1-2 *(a) Schematic representation of the basic movement operation principle of a ship, (b) Example of a real ship (Source: Ulstein. Reproduced with permission of Ulstein)*

ship. In this case again, the element that enables the rotational movement of the blades is an electric motor. Again, in order to obtain reliable and controllable movement, the thruster is controlled by an electric drive specifically designed and optimized for that individual ship, enabling the ship to move at different speeds, under different sea conditions, or to perform dynamic positioning (DP) when performing a specific task. It must be mentioned that, in ship applications, not all the ships utilize an electric motor to move the thruster. Alternatively, for instance, diesel engines can also be employed. However, this book mainly focuses on electric ship propulsion, which is the most commonly used propulsion technology.

On the other hand, we can mention the electric vehicle application. In this case, as schematically illustrated in Fig. 1-3, the linear advance of the vehicle is created by the rotational movement of the traction

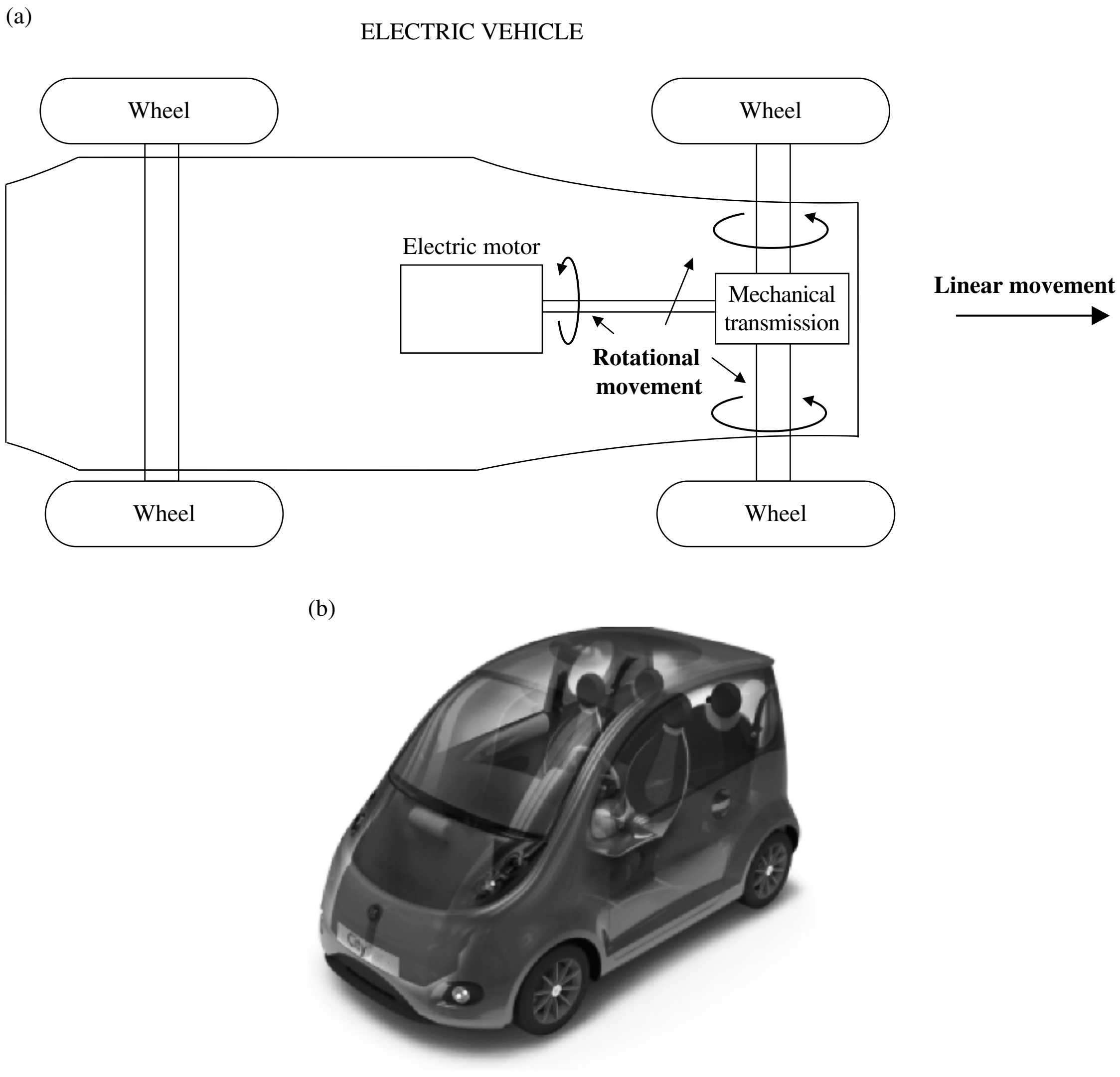


Fig. 1-3 *(a) Schematic representation of the basic movement operation principle of an electric car, (b) Example of a prototype of electric car*

wheels, which are driven by an electric motor. Again, as occurs in the previous two applications described, in order to obtain good longitudinal advance performance, an electric drive is employed, enabling features of the electric vehicle such as: variable speed, electric brake, anti-slip performance, and efficient energy consumption.

In a similar way, it is possible to study vertical transport applications.

Thus, for instance, in many buildings in our cities the elevators have become almost a necessity. In Fig. 1-4, the schematic representation of the basic operation principle of an elevator is depicted. In this case, the car movement between floors must be controlled for the safe and comfortable transportation of the passengers. To this end, the linear movement of the car is generated by the combination of an arrangement of sheave, ropes, and electric motor, which transforms the rotational movement created by the electric motor into the actual linear displacement of the passengers within the car.

The present book analyzes the traction electric drives of the previously introduced four applications; however, it is possible to find a huge number of applications and devices that require an electric drive for the proper control of their movement. Table 1-1 shows some examples of applications governed by an electric drive (the description is not intended to cover all of the possible existing applications).

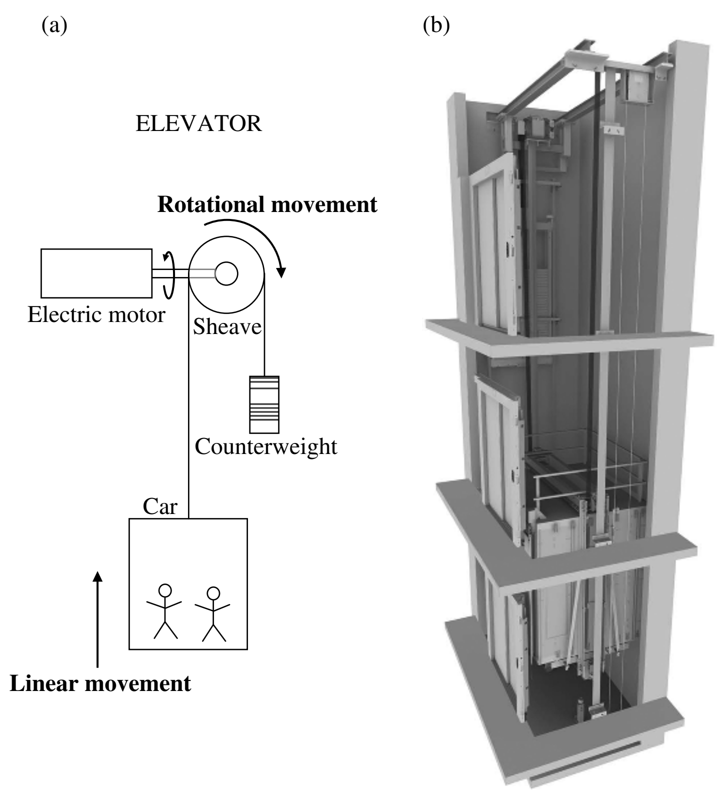


Fig. 1-4 *(a) Schematic representation of the basic operation principle of an elevator, (b) Example of a real elevator (Source: ORONA. Reproduced with permission of ORONA)*

Table 1-1 *Examples of applications and devices governed by an electric drive*

Industry applications	Mining: • Conveyors • Grinding mills • Crushers • Shovels • Water pumps • Ventilation fans • Hoists Petrochemical: • Oil pumps • Gas compressors • Water-injection pumps • Mixers Metal: • Rolling mills • Cooling fans • Coilers • Extruders • Blast furnace blowers Paper/Pulp: • Grinders • Winders • Fans • Pumps Cement: • Crushers • Draft fans • Mills
Home appliances	Washing machines Air conditioning systems Cooling systems
Energy generation	Wind turbines Wave energy Tidal energy Hydroelectric power conversion plants Geothermal energy
Machine tools	Lathes Milling machines Boring machines Drilling machines Threading machines Grinding machines

(*continued overleaf*)

Table 1-1 (*continued*)

	Machining centers
	Broaching machines
	Sawing machines
	Presses
	Robots and manipulators
Transportation	Electric vehicles
	Hybrid vehicles
	Trains
	Trams
	Elevators
	Escalators
	Ship propulsion
	Actuators in aircrafts
	Cranes

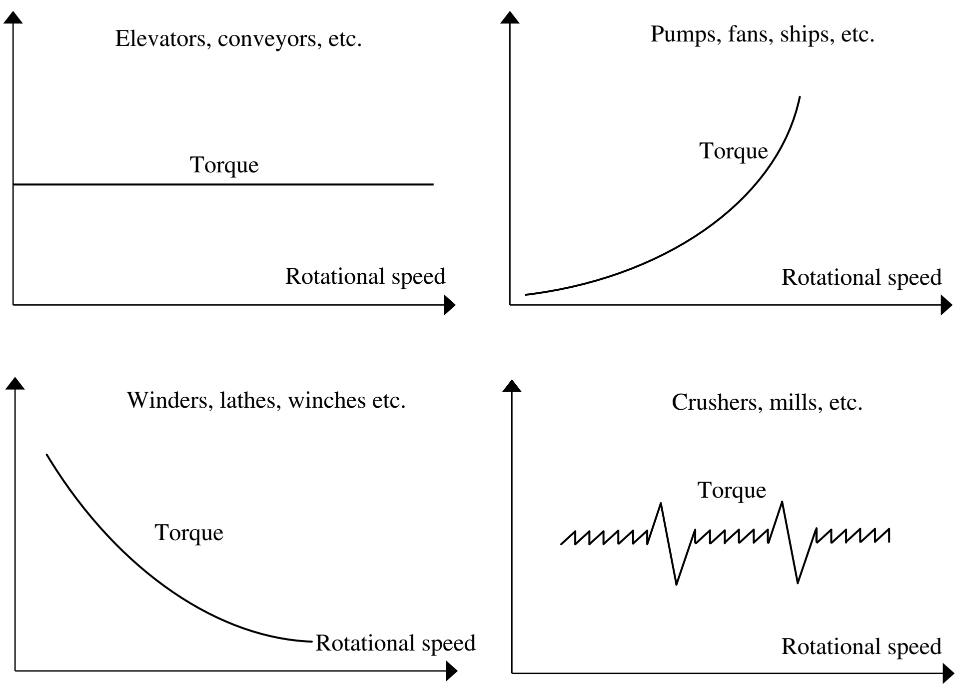


Fig. 1-5 *Torque-speed behavior of different applications*

It can be seen that there are many industry sectors and applications where electric drives of different characteristics and features govern movement.

The reader can intuit that in all of these applications, the movement that is generated needs to overcome a force or torque. Hence, this torque is seen by the electric drive, more specifically by the electric motor that must provide an opposition torque, for the proper operation of the system. Thus, for instance in elevators, the electric drive must be able to provide the required and variable torque at the motor's shaft in order to create an equivalent force to move the car, no matter the number or weight (within reason) of the passengers being transported. Or, for instance, if a train is required to move at a constant speed, the torque that the electric drive must provide to traction the wheels would depend on the force of the air that is in opposition, the slope, the weight of the passengers, etc.

Hence, depending on the nature of the application and the operating conditions of the system itself, the opposition torque that the electric drive must provide often follows a predefined pattern. Fig 1-5 illustrates some typical patterns of torque vs rotational speed of different applications. It can be noticed that the elevators, for instance, operate at constant torque for a fixed number of passengers in the car (constant mass). Or, for instance in ships, that the torque the electric drive must provide to move the thruster at different rotational speeds, and therefore to move the ship at different longitudinal speeds, has an exponential relation to the rotational speed. The physical equations describing these torque vs speed relations of the mentioned four representative applications will be derived in subsequent chapters.

1.3 Electric drives for traction applications

1.3.1 General description

As stated in the previous section, in traction applications or in applications where motion is required, the electric drive is in charge of controlling movement. Depending on the nature of the application and its characteristics in general, the electric drive is specifically designed ad hoc in order to obtain good performances and meet the application's requirements. There are many types of electric drive configurations and it is beyond the scope of this chapter to present all of them. Instead, some of the most representative electric drive configurations will be shown in this section. These representative configurations are the basic drives, which in subsequent chapters are explained and analyzed in detail regarding the following applications or devices: trains, ships, electric vehicles, and elevators. And, as stated previously, we will focus on AC electric drives, which are the most commonly employed drives in these applications.

Hence, Fig. 1-6 shows a general schematic block diagram of an electric drive. As was advanced before and can be seen in the figure, the electric drive is in charge of controlling the movement of the mechanical load. On the other hand, a source of energy that allows the exchange of power required to create and control that movement is necessary. Thus we can distinguish the following main elements [1], [2], [3], [4]:

- Mechanical load: Depending on the application, this is the mechanical compendium of elements which are involved in the movement of the system or device. Thus, for instance, in an elevator, the mechanical load is the compendium of the passengers, the car, the ropes, and the sheave. Or, for instance, in an electric vehicle, the mechanical load is the compendium of the road characteristics, the wheels, the vehicle dimensions and weight, and the number of passengers, etc. As seen in Fig. 1-5, most of the applications require an adjustable speed and torque control.
- Energy source: From this element, the electric drive takes the energy necessary to create the movement. Depending on the nature of the application, the energy flow can be exclusively unidirectional, from the energy source to the load (fans, blowers, etc.), or from the mechanical load to the energy source (wind energy generators, etc.). Alternatively, the power flow can be bi-directional in some applications (electric vehicle, trains, etc.), which means that, depending on the operating conditions, the energy flow can go, at certain times, from the source to the load and, at others, from the load to the source.

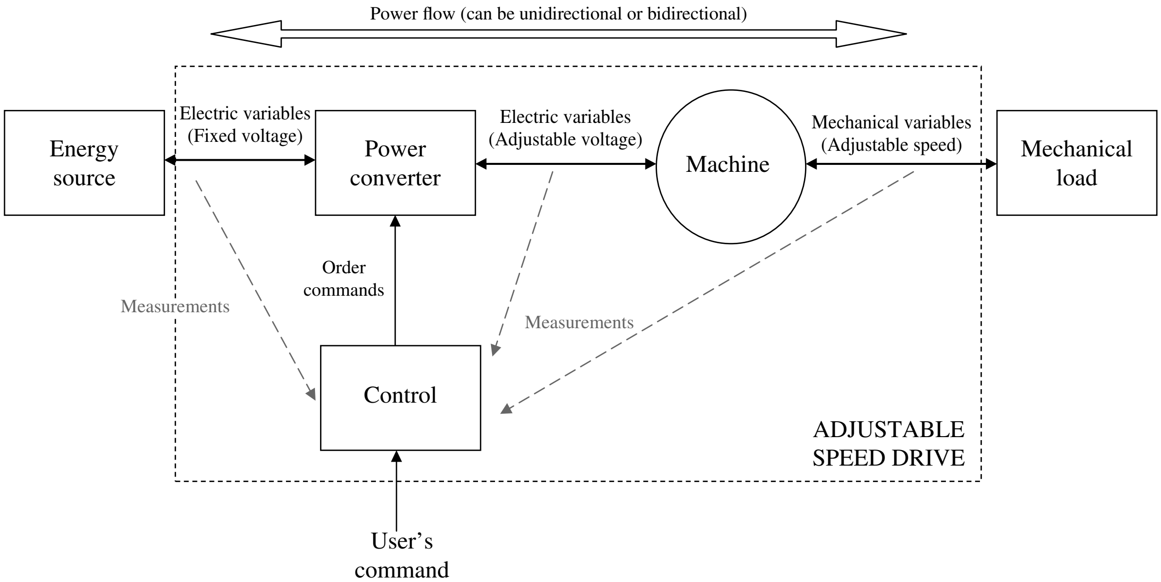


Fig. 1-6 *Schematic block diagram representation of an electric drive*

- Electric drive: As mentioned before, the electric drive in general is composed of many elements; however, probably the most important ones are the following:
  - The electric machine: The electric machine is the element which provides the rotational speed and torque to the mechanical load to assure the correct movement of the system. As will be seen later, there are different types of electric machine configurations (or topologies). In order to be able to obtain adjustable speed performances, the machine must be supplied at adjustable voltage operation conditions.
  - The power electronic converter: The electric machine must be appropriately supplied to be able to provide proper torque and speed at the shaft. The element which is in charge of supplying the electric machine is the power electronic converter and is connected to the energy supply. It is able to supply the required adjustable voltage to the electric machine, converting the voltage from a normally fixed voltage supplied by the energy source. As will be seen later, there are different types of power electronic converter configurations (or topologies).
  - The control: In general, the power electronic converter is governed by a control algorithm (often simply called control) that allows key variables of the electric drive—such as rotational speed, torque, and currents—to be controlled. The control algorithm needs to continuously measure certain variables of the electric drive (electrical and/or mechanicals), in order to be able to control the user's defined command, owing to efficiency or security reasons. Thus for instance in an electric vehicle, the user defines with the pedal the acceleration torque of the vehicle. The control algorithm will be in charge of defining the necessary adjustable voltage that the power converter must provide, so the electric motor responds to the demanded acceleration of the vehicle. As in the previous two elements of the drive, depending on the application (and therefore the machine and converter employed), there are different types of algorithms, which are described later.

Therefore, as has been mentioned repeatedly, the electric machine produces the required rotational speed and torque by the load at the shaft. For that purpose, if the torque and/or speed must vary during the operation, it is necessary to supply the machine with adjustable AC voltage, as depicted in Fig. 1-7. Nowadays, the most efficient, reliable, and cost-effective electric machines are AC machines; therefore, the required adjustable supplying voltage is AC. This means that the supplying voltage can present different amplitude and frequency, as is schematically represented in Fig. 1-7. Note that the electric machine can be conceived as an electromechanical converter, which on one, electrical, side operates with electric variables such as voltages and currents, while on the other, mechanical, side operates with mechanical variables such as torque and rotational speed.

On the other hand, the element that can produce the required adjustable AC voltages for the electric machine is the power electronic converter. As is schematically represented in Fig. 1-8, the power converter in general in an electric drive converts fixed voltage from the energy source into an adjustable AC voltage required by the machine. Depending on the characteristics of the application, it is possible to find energy sources of DC fixed voltage or AC fixed voltage. Thus, depending on the nature of the energy source, the nature or configuration of the power converter would be different as well. To carry the proper conversion from DC to AC, the power converter receives, continuously, order commands from the control algorithm.

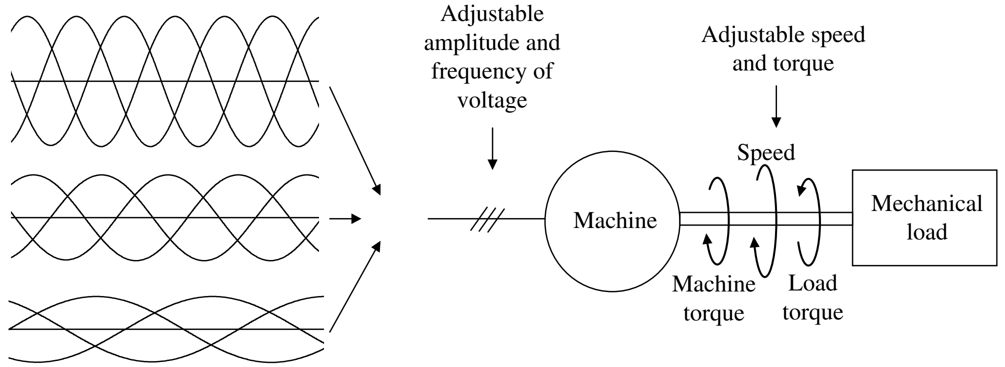


Fig. 1-7 *Electric machine and mechanical load interaction*

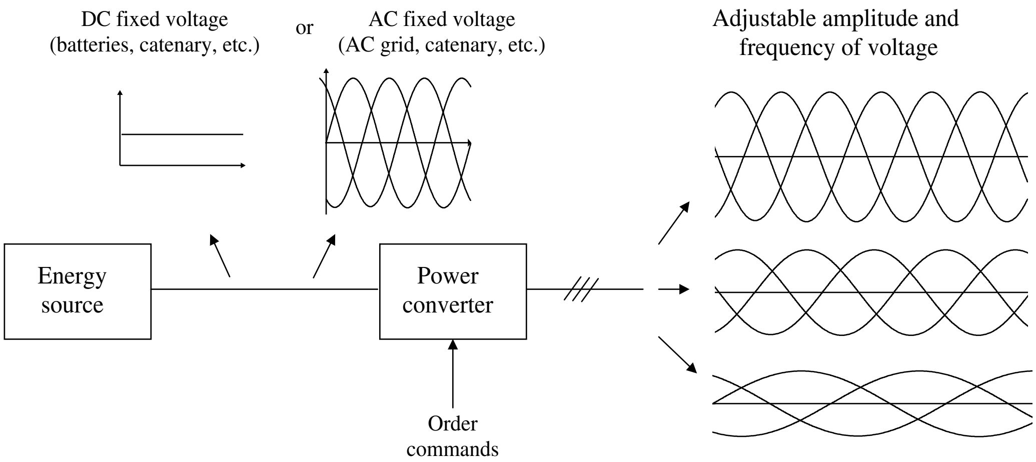


Fig. 1-8 *Interaction between the energy source and the power converter, to supply the electric machine*

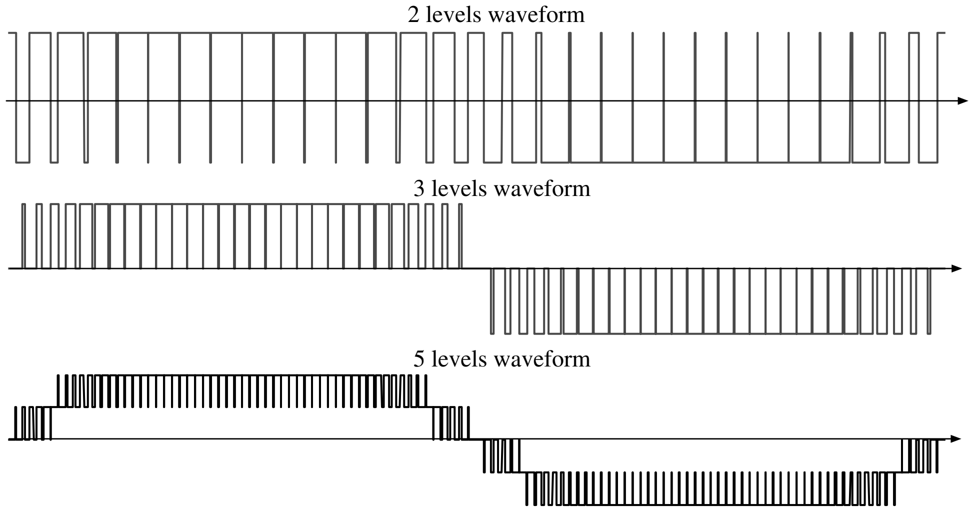


Fig. 1-9 *Output AC voltages obtained by different converter topologies with different voltage levels*

It must be highlighted that, ideally, the AC machines would require sinusoidally shaped voltages of different amplitude and frequency to properly operate. However, at least nowadays, the most efficient and cost-effective power electronic converters are not able to produce ideal sinusoidally shaped voltages. Instead, the power electronic converter at their AC side is able to create staggered or chopped voltages, with a different similitude degree from the sinusoidal ones. As represented, in a simplified form, in Fig. 1-9, depending on the power electronic converter configuration, or topology, it is possible to create voltages of different constant levels that present different similitude appearance from the ideal sinusoidal voltage. Thus, it can be noticed how if the number of voltage levels employed is high (five in this example), the similitude to the sinusoidal shape is closer than if the employed number of levels is low (two in this example). Hence, it can be said that with this type of staged voltage waveforms the electric machines are good enough and therefore useful, providing an acceptable performance of torque and speed behaviors for most of the applications described in this chapter.

The power electronic converter is normally composed of different types and numbers of controlled and uncontrolled switches, also called semiconductors. In addition, passive elements such as, most commonly, capacitors and, less so, inductors are also present at the converter. Depending on the disposition and number of the switches employed, the shape of the output AC voltage that can be obtained is different. By controlling the switches of the power electronic converter, the output voltage waveform of the converter is also controlled. Depending on how the switches of the converter are disposed or arranged, it is said that a different power electronic converter topology is obtained. Typically, the uncontrolled switches employed are the diodes, while the controlled switches employed can be: insulated-gate bipolar transistors (IGBTs), metal-oxide-semiconductor field-effect transistors (MOSFETs), insulated-gate controlled thyristors (IGCTs), and so on. Fig. 1-10 gives a schematic representation of a diode and an IGBT.

On the other hand, as mentioned before, the power electronic converter is continuously governed by the control algorithm. In general, as schematically represented in Fig. 1-11, the control algorithm receives a user's command that can be speed, torque, power, and so on. depending on the nature of the application. This command or reference can change according to the user's needs or the needs of the application at a given moment. Then, considering different measurements taken from the electric drive itself (currents, position, or speed of the shaft, etc.), the control algorithm creates order commands for the controlled switches of the power electronic

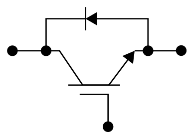


Fig. 1-10 Schematic representation of a diode and an IGBT

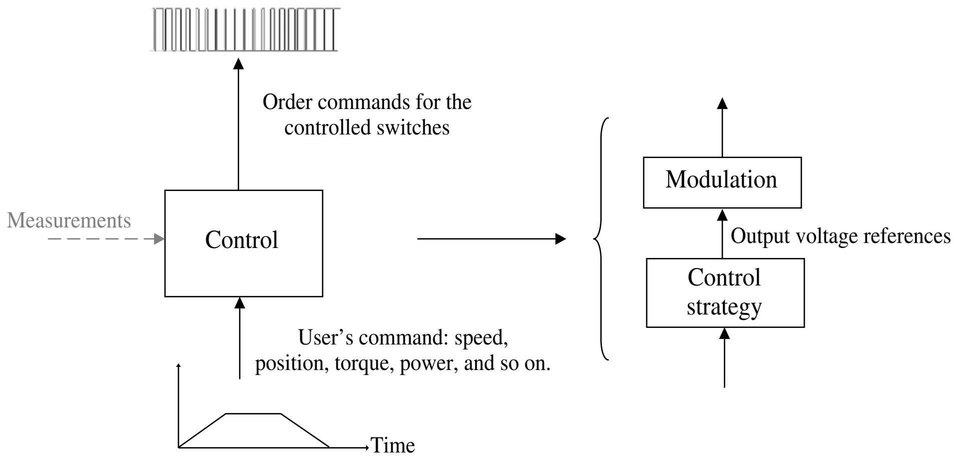


Fig. 1-11 Schematic representation of the control algorithm of an electric drive

converter, which produces the necessary output AC voltage to respond to the user's command. There are many different types of control algorithm, adapted to meet the needs of elements such as: the application, converter topology, machine topology, nature of the energy source, etc. However, it can be affirmed that the most popular or commonly employed control algorithms are divided into two different parts, or tasks. The first one can be called the control strategy. In general, by following basic principles of control theories, it creates the voltage references at the AC output, for the second part (i.e. the modulation). The modulation creates the order commands for the controlled switches, based on the voltage references provided by the control strategy.

1.3.2 Different electric drive configurations

The previous section provides an intuitive approach to the electric drive. In this section, a more detailed description of the electric is given, showing the most important configurations that can be found in the applications discussed in this chapter. The electric drive configurations are presented, attending to the type of power electronic converter that is used. They are presented as general electric drives, which are suitable for many applications.

1.3.2.1 Electric drive with a DC/AC power converter

The first electric drive configuration that is presented is depicted in Fig. 1-12. The electric machine is supplied by a DC/AC converter that takes the energy from a fixed DC voltage source. The most common DC sources can be batteries or DC catenaries in railway traction applications.

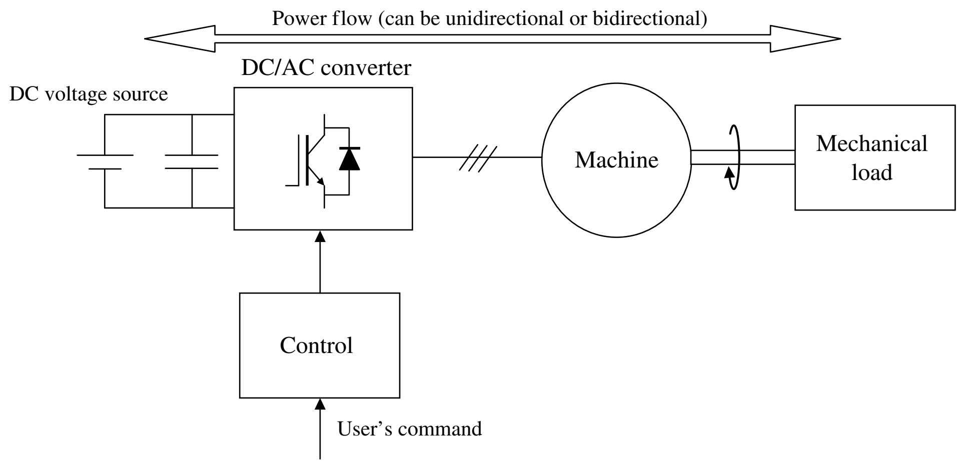


Fig. 1-12 Basic electric drive configuration with a DC/AC converter

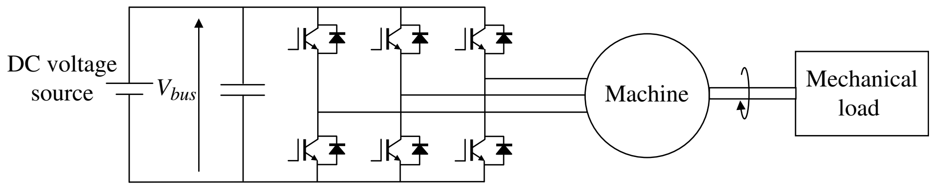


Fig. 1-13 Basic electric drive configuration with a classic two-level DC/AC converter topology

Although ideally the DC source is of fixed voltage, it must be said that the real batteries or catenaries vary their voltage, depending on several factors. Because of this, this type of electric drive configuration must be specially prepared to handle DC voltage bus variations that can take extreme values in some cases. On the other hand, with respect to the DC/AC power electronic converter, probably the most common topology employed nowadays is the classic two-level converter, which is presented in Fig. 1-13. In this case, IGBTs have been used as controlled switches, but some other types of controlled switches could optimize the converter performance depending on the needs of the applications where this electric drive is used. It can be seen that, in this configuration, a capacitor is typically located in parallel to the battery (or battery pack), in order to obtain several performance improvements of the drive, which is more deeply described in subsequent chapters.

In principle, depending on the nature of the application (the mechanical load), this configuration can transport energy in both directions, from source to load and from load to source—at least if the energy source is prepared to receive energy, since the power converter is bi-directional. With regards to the converter topology, it is also possible to use a more sophisticated power converter topology as, for instance, the three-level neutral point clamped (3L-NPC) topology, the four-level flying capacitor (4L-FC) topology, or the five-level active neutral point clamped (5L-ANPC) topology. One leg of these multilevel topologies is represented in Fig. 1-14. It must be mentioned that this is just an example of the types of modern multilevel converter topologies that can be suitable for this electric drive, and used in some of the applications described in this chapter. By employing multilevel converter topologies, although the complexity of the converter is increased, there are some useful

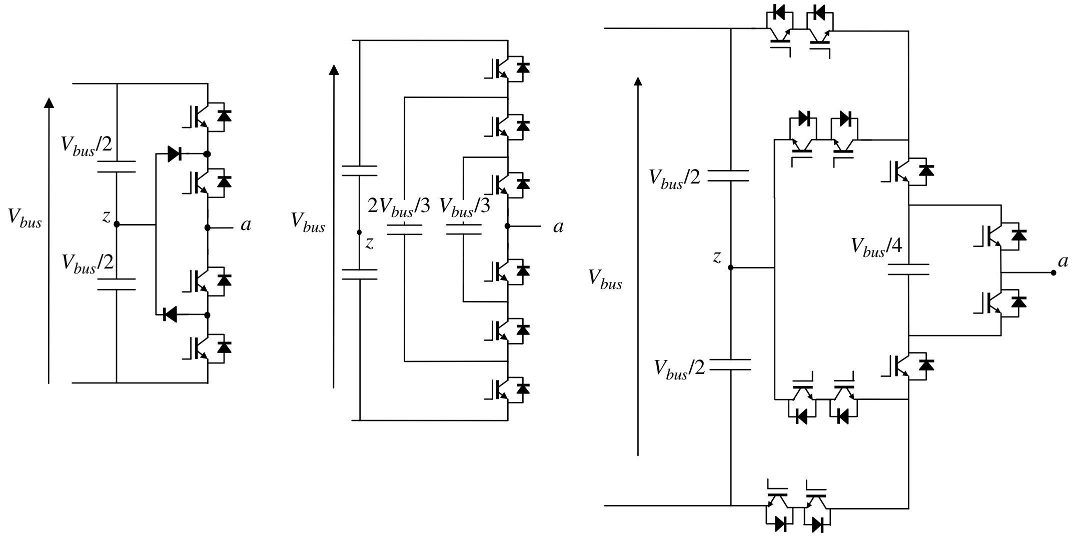


Fig. 1-14 *One arm of the following multilevel converter topologies (from left to right): 3 L-NPC topology, 4 L-FC topology, and 5 L-ANPC topology*

benefits that can also be obtained: they operate at higher voltage to reduce the amount of current employed, improve the output waveform quality, and so on.

Finally, Fig. 1-15 illustrates the shape of the output AC voltages obtained with each of the multilevel converter topologies mentioned.

To conclude, with regards to the machine topology, it can be said that this electric drive allows the use of any kind of AC machine, which obviously requires AC voltages at the input. Subsequent sections of this chapter show that there are different possible machine topologies, but probably the most employed ones are induction machines and synchronous machines as commented before.

1.3.2.2 Electric drive with a DC/DC/AC power converter

The electric drive configuration presented in this section, compared to the one presented in previous section, incorporates a DC/DC converter in order to mainly stabilize the DC voltage at the input of the DC/AC converter. The basic scheme configuration is depicted in Fig. 1-16. Thus, the inclusion of this converter can be useful if the DC source is going to vary its voltage during normal operation. In this way, the DC/DC converter stabilizes the voltage at the output, allowing the operation of the DC/AC converter at constant DC voltage and, therefore, optimizing its performance. In a similar way, the incorporated DC/DC converter can also be useful when the DC source voltage is too low to synthesize the required AC voltage. In this situation, the DC/DC converter increases the DC voltage, thus allowing the proper operation of the system. Here again, at least if the energy source is prepared, the power flow can be bi-directional, depending on the nature of the application. With regards to the DC/AC converter topology, in this case again, it is possible to use a two-level converter topology and a multilevel converter topology as well.

On the other hand, this electric drive configuration needs an extra control for the additional DC/DC converter included, which typically is in charge of ultimately controlling the DC voltage at the input of the DC/AC

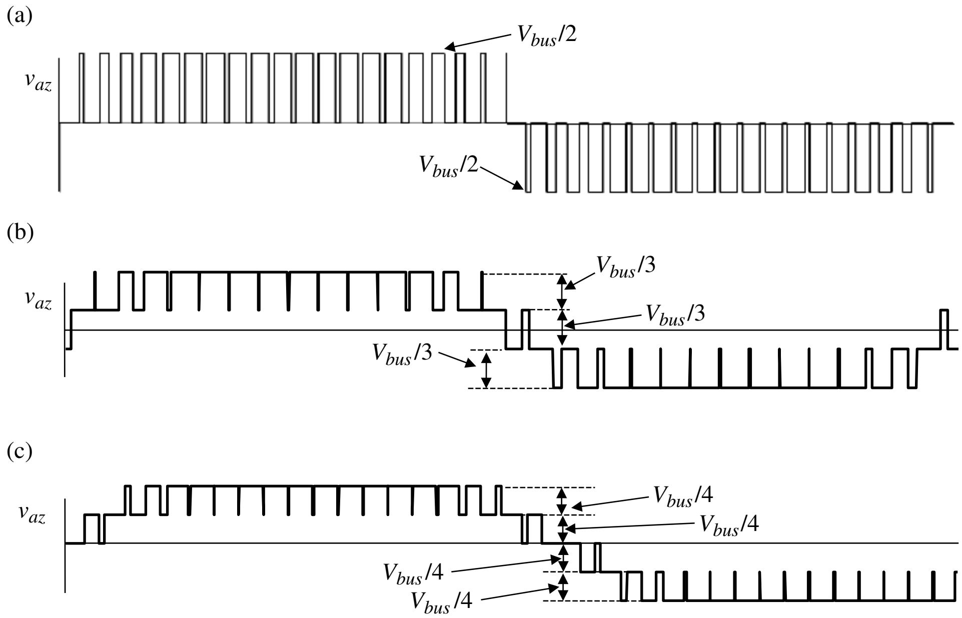


Fig. 1-15 *Output voltages of (a) 3L-NPC, (b) 4L-FC, and (c) 5L-ANPC topologies*

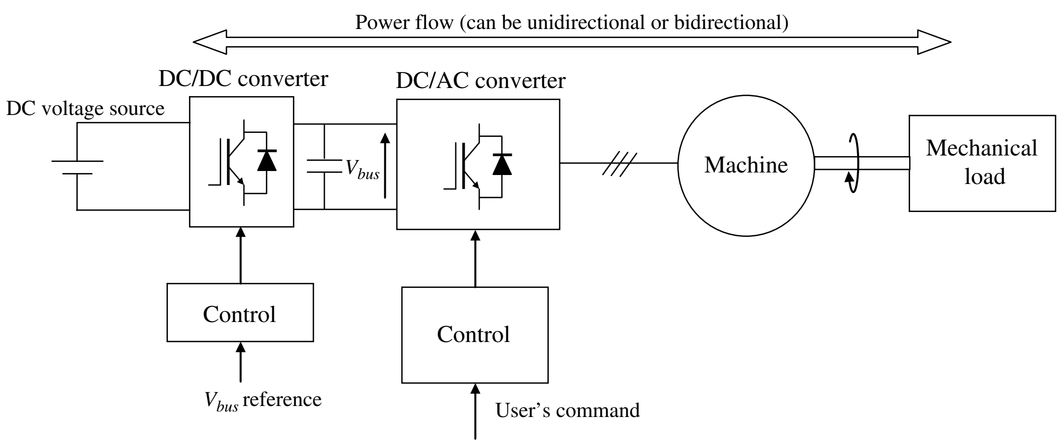


Fig. 1-16 *Electric drive configuration with a DC/DC/AC converter*

converter. One example of a suitable DC/DC converter configuration is depicted in Fig. 1-17 together with a two-level converter as DC/AC converter topology. This configuration allows for the transmission of energy in both directions. Chapter 5, related to railway traction, and Chapter 7, related to electric vehicles, provide more details about DC/DC converters. Finally, with regards to the electric machine topology, this drive is also suitable for electric machines such as induction machines or synchronous machines.

On the other hand, Fig. 1-18 illustrates the auxiliary pre-charging circuit that typically accompanies the DC voltage sources, for instance battery packs. As the reader may notice, the DC source cannot be suddenly connected

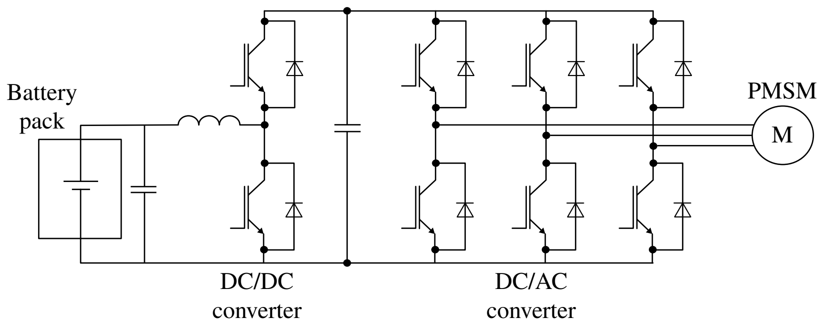


Fig. 1-17 *Example of a possible DC/DC converter*

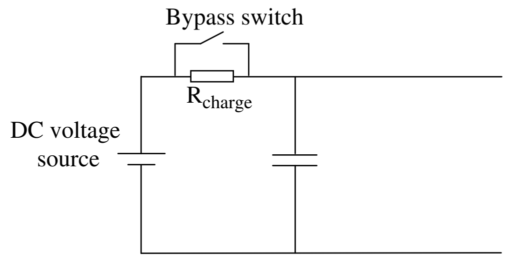


Fig. 1-18 *Charging resistance and bypass switch to avoid damaging the capacitor and batteries*

to the capacitor, because a high current transient would occur. In order to avoid this, a resistance is normally placed when connected, while after a time when the capacitor is charged the resistance is disconnected by means of the bypass switch. In battery packs, as is shown in Chapter 7, related to the electric vehicle, the charging circuit is often incorporated by the manufacturer of the battery pack itself. On the other hand, the necessity of incorporating the capacitor arises to smooth the current shape demanded from the battery pack, therefore increasing its life.

1.3.2.3 Electric drive with a unidirectional AC/DC/AC power converter

The next electric drive configuration takes its energy from an AC voltage source. For this purpose, it requires an AC/DC converter at the input. Then, a DC/AC converter is used, as in the previous two electric drive configurations. The schematic block diagram of this drive is depicted in Fig. 1-19. It shows that the two converters employed form an AC/DC/AC converter configuration.

In this case, a passive front end is employed at the input. It is a diode bridge rectifier, which converts the voltage from the AC fixed voltage amplitude of the source to a fixed DC voltage. This converter is composed solely of diodes and so needs no control algorithm. It is not reversible, which means it is able to transmit the energy only from the AC side to the DC side. It can be single-phase or three-phase, depending on the nature of the grid where it is connected. Consequently, this drive configuration is not suitable for generation applications, since it would not be able to take energy, for instance, from a wind turbine's blades and send it to the electric grid. Fig. 1-20 illustrates two possible configurations for the input AC/DC diode bridges. One is used when the applications oblige it to use a single-phase AC source and the other for AC sources which are

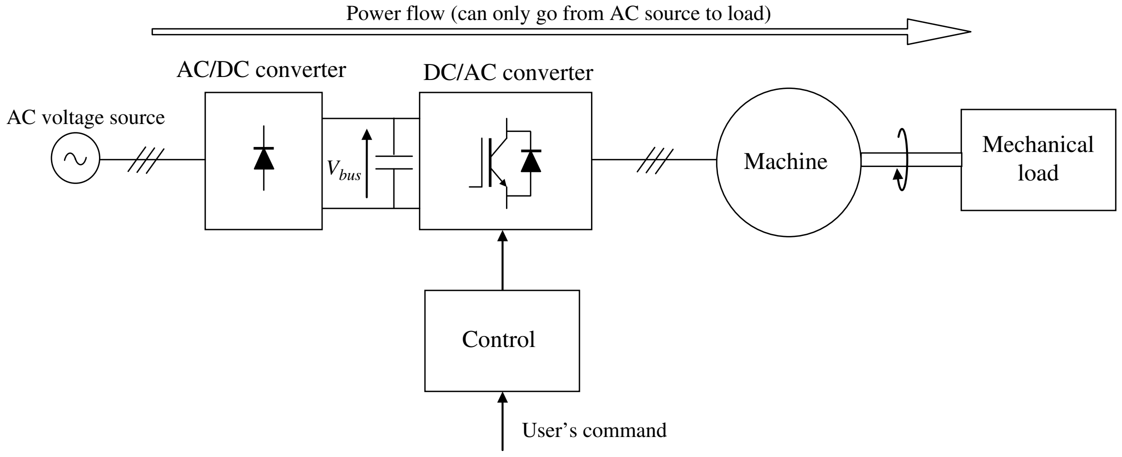


Fig. 1-19 *Electric drive configuration with a uni-directional AC/DC/AC converter*

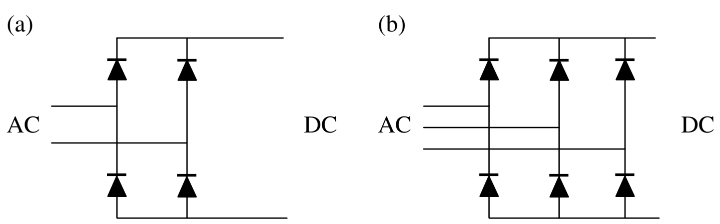


Fig. 1-20 *Two diode bridge converter configurations: (a) single phase diode bridge and (b) three-phase diode bridge*

three-phase. In Chapter 6, which is dedicated to ship propulsion, more diode-based AC/DC converters, which enhance performance, are discussed. On the other hand, it must be remarked that often, a step-down transformer (either single-phase or three-phase) can be employed at the input of the electric drive in order to adapt the voltage level of the AC source and the required electric drive AC input voltage. In this exposition, it has not been represented in Fig. 1-19, for simplicity's sake, and because it is not always needed. In addition, often also in this electric drive configuration, an AC filter is also included at the input of the diode rectifier. The filter topology often consists of a simple inductance per phase. The inclusion of this filter allows a better-quality current exchange with the grid to be obtained. The filter is often not physically placed when a transformer is needed at the input. Instead, the transformer is designed specifically with the necessary leakage inductance, which also provides the filter functionality.

The fixed relation between the AC voltage input (V_{LLrms}) and the obtained DC voltage output of a three-phase diode bridge is:

$$V_{DC} = 1.41 \cdot V_{LLrms} \tag{1.1}$$

This is valid when a sufficiently high capacitance is placed at the DC side, at the input of the DC/AC converter. When the AC source is single phase, the relation follows exactly the same equation, but in this case the AC voltage input is not line-to-line (LL) but is single phase.

With regards to the DC/AC power electronic converter, it is possible to employ all the topologies mentioned in the previous two electric drive configurations (i.e. from the classic two-level converter to the more modern and sophisticated multilevel converters). The electric machine can also be a synchronous machine or an induction machine, depending which fits better in the corresponding application.

It must be highlighted that when the application needs to operate in generator mode, working as an electric brake, it is necessary to incorporate a DC chopper (also called a crowbar) at the DC bus, which allows the regenerative energy in a resistance at the DC side of the AC/DC/AC converter to dissipate. One example of an electric drive configuration with a diode bridge rectifier and a two-level inverter incorporating a DC chopper is depicted in Fig. 1-21. The DC chopper is typically mainly composed of a controlled switch and a resistance. It works in such a way that the controlled switch is activated enabling the regenerative energy that comes from the machine at the resistance to dissipate. This occurs when an increase of the DC voltage of the AC/DC/AC converter is detected. Conversely, it is deactivated when the DC bus voltage goes down again taking normal values, because the machine stops operating as a generator.

In addition, Fig. 1-22 illustrates the DC chopper arrangement needed for the DC bus capacitors of a three-level converter. For multilevel converters of a higher order, with bigger number of capacitors at the DC bus, it would be necessary to place one DC chopper for each capacitor, to ensure the integrity of all the capacitors.

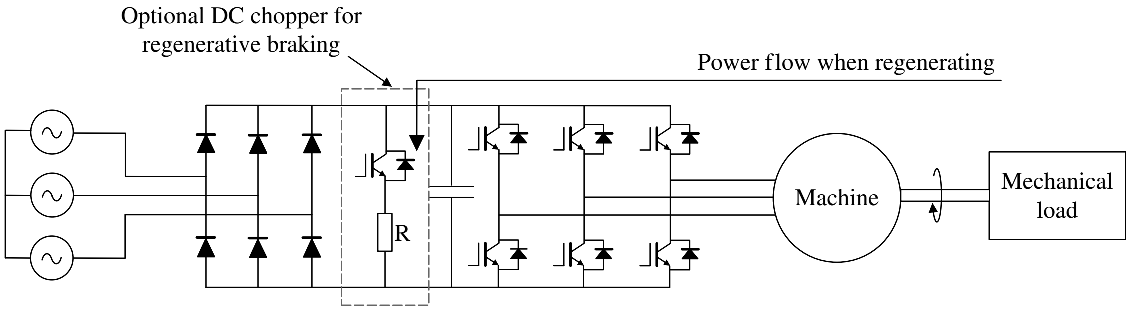


Fig. 1-21 *Electric drive configuration with a uni-directional AC/DC/AC converter (diode bridge rectifier and two-level inverter) incorporating a DC chopper (or crowbar)*

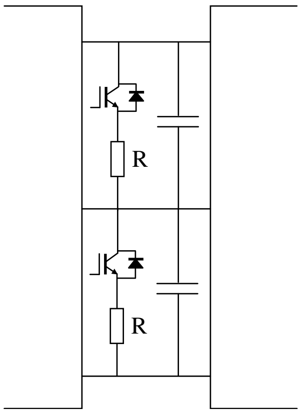


Fig. 1-22 *DC choppers for the DC bus capacitors of a three-level converter*

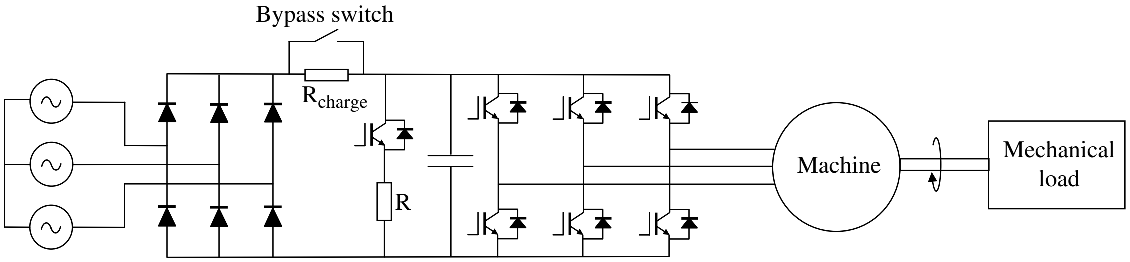


Fig. 1-23 *Electric drive configuration with a unidirectional AC/DC/AC converter (diode bridge rectifier and two-level inverter) incorporating a DC chopper and a charge resistance for the initial charge of the DC bus capacitor (charge resistances can also be placed at the AC side, instead of the DC side)*

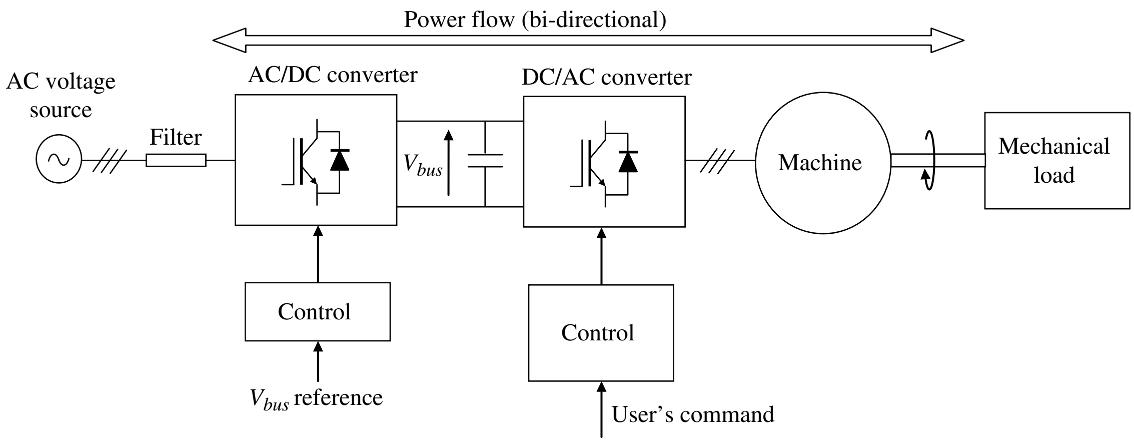


Fig. 1-24 *Electric drive configuration with a bi-directional AC/DC/AC converter (input converter can also be single phase)*

Finally, it must be mentioned that this configuration of electric drive needs an auxiliary circuit for an initial charge of the DC bus capacitor through the diodes of the input rectifier, as occurs in DC/DC/AC converter configurations. Fig. 1-23 illustrates the charging circuit that is simply configured by a charging resistor (R_{charge}) and a bypass switch. Thus, in an initial maneuver, the capacitor is charged from zero to a certain DC voltage through the diodes and the resistance, avoiding a high overcurrent. Then, once the DC bus voltage reaches a certain value, the R_{charge} is bypassed by the bypass switch, allowing the entire AC/DC/AC converter to start its operation in a normal regime. Alternatively, it is possible to find also auxiliary charging circuits that incorporate charging resistances at the AC side of the diode rectifier.

1.3.2.4 Electric drive with a bi-directional (regenerative) AC/DC/AC power converter

A more complex and sophisticated electric drive configuration than the one presented in the previous section is the drive that incorporates a bi-directional (also called regenerative) AC/DC/AC converter. A schematic representation of the drive is depicted in Fig. 1-24. As can be seen, an active front end is used as the AC/DC converter, enabling the regeneration mode to the grid. Thus, instead of using a diode rectifier, as in the previous

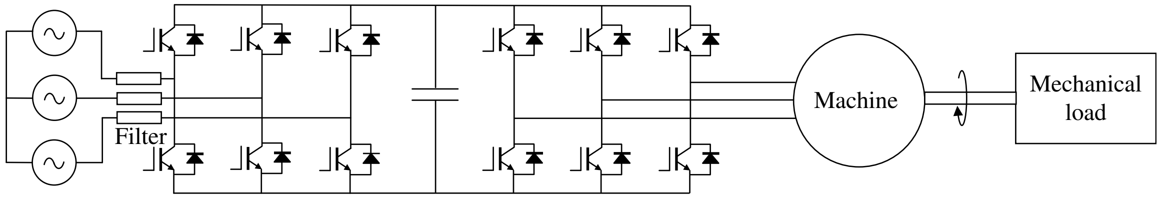


Fig. 1-25 *Electric drive configuration with a bi-directional AC/DC/AC converter using two-level converters as rectifier and inverter with a three-phase grid*

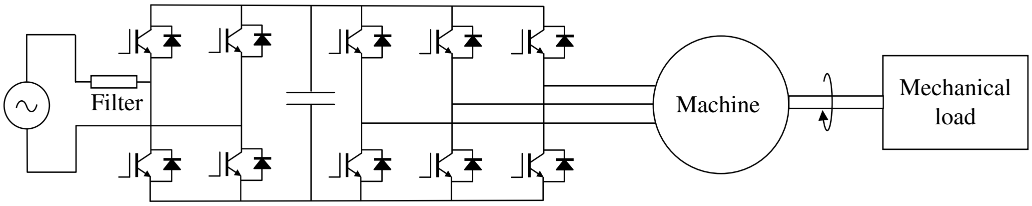


Fig. 1-26 *Electric drive configuration with a bi-directional AC/DC/AC converter using two-level converters as rectifier and inverter with a single-phase grid (the charging auxiliary circuit is often included at the AC side)*

drive, a controlled AC/DC converter is used with its corresponding control algorithm. In general, the topologies of the AC/DC converter and the DC/AC converter are equal. Therefore, if, for instance, a 3L-NPC converter were wanted, it would be employed at both sides of the same topology. In addition, the input AC/DC converter requires a filter at the AC side for the proper operation of the system. The typical filter configurations are: pure inductive filters (L), or combinations of inductances and capacitances (LC or LCL). Hence, the AC/DC converter at the input is able to work in a regenerative mode, regenerating energy from the mechanical system to the grid. Typically, the AC/DC converter at the input is controlled in such a way that it is in charge of controlling the DC bus voltage. A detailed study of this converter and its control is provided in Chapter 4.

Note that, in this configuration, it is not necessary to use the DC chopper, since the regenerative energy is delivered to the grid. Obviously, this configuration of electric drive is suitable when the grid is connected and prepared to receive energy as well as to provide energy. The reader can deduce that this configuration is typical in energy generation applications such as wind turbines, for instance. In this configuration again, the converter at the input can be single-phase or three-phase, depending on the characteristics of the application. Again, a step-down transformer can also be included at the drive, if the voltages of the AC grid source and the voltage of the drive do not match. As in previous configurations, the converter topologies can be a classic two-level or multilevel converter topology. Also with regards to the type of machine, an induction machine or a synchronous machine can be used, depending on the characteristics of the application.

Finally, Fig. 1-25 illustrates an example of electric drive with bi-directional AC/DC/AC converter, using two-level converters as rectifier and inverter and connected to a three-phase grid. In this case, as with the previous drive configuration, the pre-charge of the capacitor is done across the diodes of the input converter and the charging resistances are often located on the AC side.

In some applications, for instance in railway traction with AC catenaries, the grid is not available with three phases. Therefore, in these situations a single-phase input converter is necessary, as depicted in Fig. 1-26.

Alternatively, when the required output power is in the range of multi-megawatts, the parallelization of converters is often used to construct the drive. For instance, in industrial applications and sometimes in ship propulsion, it is quite common. Fig. 1-27 illustrates some examples of converter parallelization.

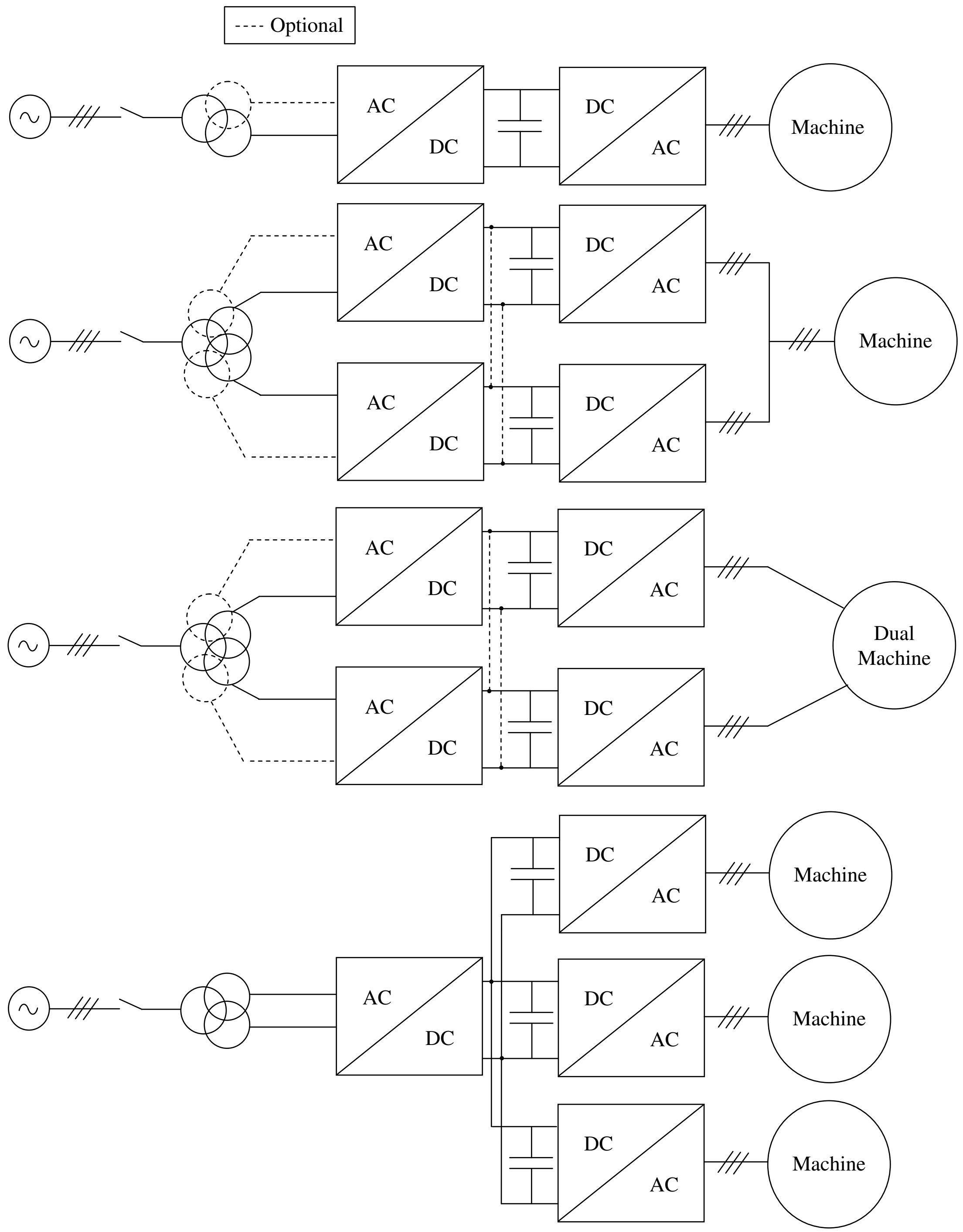


Fig. 1-27 *Electric drive configuration for high power applications with parallelization of converters [5]*

1.3.2.5 Electric drive with other power converter topologies

The most employed electric drives are presented in previous sections. This section examines some drives which are not so established in real applications, but could be of interest in the future or simply are used by a low proportion of drive manufacturers in the world. Amongst them, probably the one most studied at research level is the electric drive based on the AC/AC converter without DC-source storage in the middle of the converter (i.e. without a capacitor). These types of power converters are typically called matrix converters. They use in general a higher amount of controlled semiconductors and diodes when arranging different matrix converter topologies. One schematic example of electric drive with an AC/AC matrix converter is depicted in Fig. 1-28.

In general, these types of converters are bi-directional in terms of their power flow transmission capabilities. Since they do not transform the voltage into DC at the middle of the converter stage, they synthesize the output voltage at the machine terminals from the input AC voltage of the energy source. The converter side connected to the AC source, as in previous converter configurations, can be single-phase or three-phase.

There exist many matrix converter topologies that are beyond the scope of this book. The reader can find, in specialized literature, different constructions of matrix converters, as well as the advantages and disadvantages of the more classic converter arrangements shown in previous subsections. Fig. 1-29 shows a schematic representation of a direct matrix converter.

On the other hand, some other electric drive configurations employ a different conversion philosophy and they are quite well established in industry applications, especially in high-power applications. These types of drives are the current source converter (CSC) based electric drives. The electric drives described in the previous sections are commonly called voltage source converters (VSC), since they work and supply the loads as voltage sources. One example of a CSC-based bi-directional electric drive is depicted in Fig. 1-30. It is composed of two two-level CSCs as rectifier and inverter. It will be noted that this converter configuration only uses controlled switches (and not diodes). In this case, they use symmetrical gate-commutated thyristors (GCTs) connected in series, in order to achieve a higher operating voltage and therefore also power. They typically need a capacitor-based filter both at the input and at the output, as well as an inductive filter at the DC-link of the current converters. The reader can find more detailed descriptions of these types of converter configurations in specialized literature.

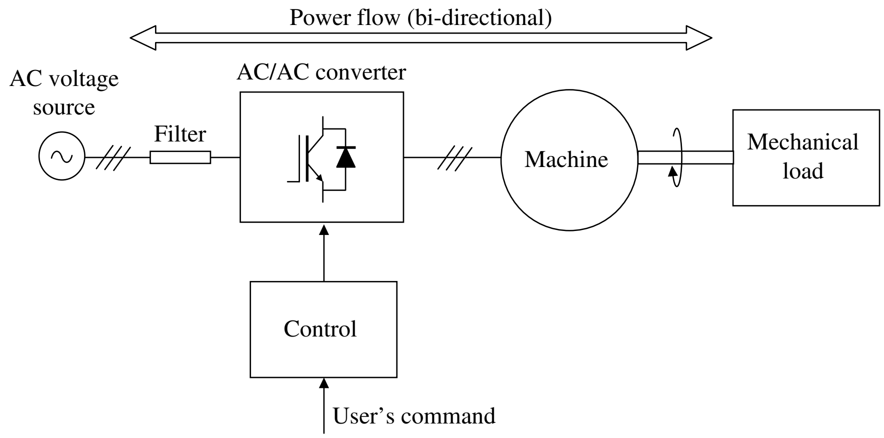


Fig. 1-28 *Electric drive configuration with a bi-directional AC/AC matrix converter*

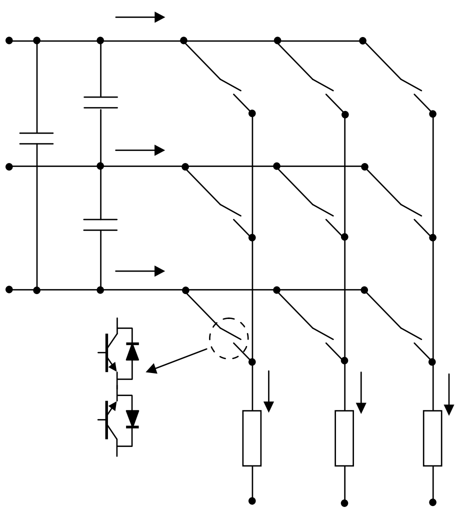


Fig. 1-29 Schematic representation of a direct matrix converter

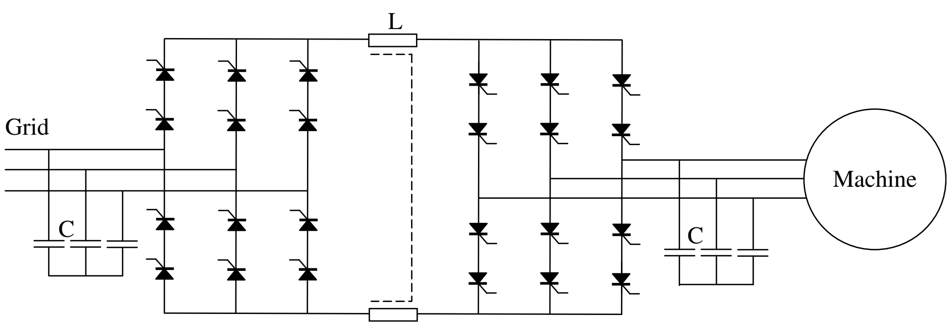


Fig. 1-30 One example of a CSC-based bi-directional electric drive

Finally, it must be said that the reader can find in specialized literature many different electric drives based on many different power electronic converter configurations not presented in this chapter—or in this book. It is beyond the scope of this book to summarize all of them. Instead, this chapter gives a short overview of the ones most employed.

1.3.2.6 Common mode currents

Common mode voltage results from the operation of the power converter with a switching pulse-width modulation (PWM) pattern. Thus, common mode voltage refers to the voltage between the neutral point of the three-phase star connected load (electric motor) and the potential of the protective earth [1]. Fig. 1-31 illustrates the equivalent circuit for a three-phase power converter with a motor, cable, and grid supply showing the parasitic capacitances. In this way, the appearance of the common mode output voltage of the converter and

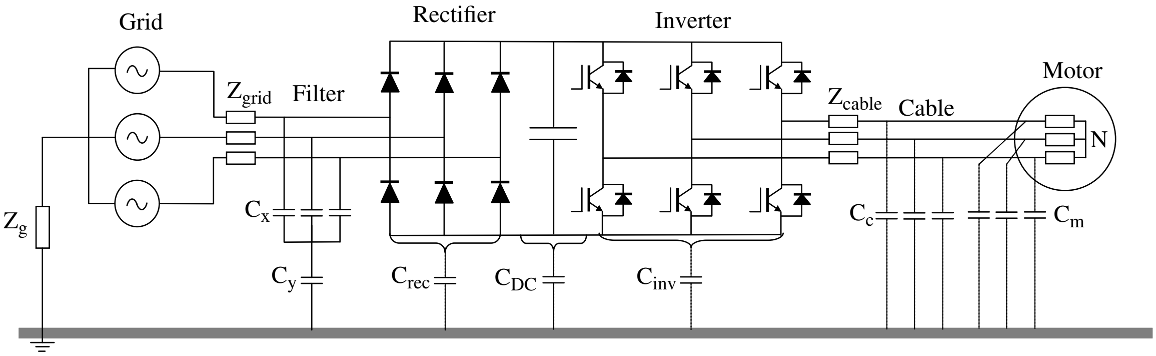


Fig. 1-31 *Equivalent circuit for a three-phase power converter with a motor, cable and grid supply showing the parasitic capacitances [1]*

the presence of parasitic capacitances in the motor and other elements of the electric drive cause the flow of zero-sequence currents.

Therefore, common mode voltages generated by the converter, with high dv/dt, produce common mode currents that often inevitably generate current bearings and shaft voltage in the motor. In general, these shaft and bearing currents through the motor cause accelerated degradation of the motor, among other undesired phenomena. It must be mentioned that there exist several types of bearing currents—such as capacitive bearing current, electric discharge bearing current, circulating bearing current or shaft current—related to the shaft voltage effect and rotor ground current. These currents are related to different physical phenomena.

In order to avoid or at least prevent these damaging currents, it is very important to reduce the influence of common mode voltages by a proper cabling and earthing system. When this is fulfilled, the further reduction of common mode currents can be obtained by increasing the impedance to these currents. Some possible solutions, often incorporated at the electric drive, are listed below [1]:

- ceramic bearings
- common mode passive filters
- systems for active compensation of common mode voltage
- decreasing the converter switching frequency if possible
- motor shaft grounding by using brushes
- conductive grease in the bearings
- common mode choke
- use of one or two insulated bearings
- use of one or two ceramic bearings
- dv/dt filter
- shielded cable for motor supply.

Therefore, in Fig. 1-32, two of those solutions are graphically represented. The common mode choke is typically constructed with three symmetrical coils on a toroidal core, as shown in the figure. The choke presents negligible impedance for differential mode currents, because the total flux in the core is eliminated for three-phase symmetrical currents. However, the impedance seen by the common mode current is important.

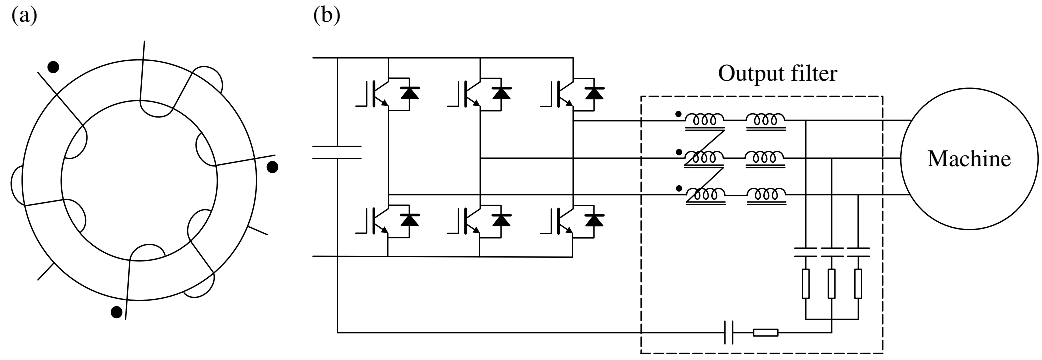


Fig. 1-32 *Two examples of passive solutions for reducing common mode currents: (a) common mode choke and (b) common mode output filter*

On the other hand, the example of common mode passive filter [1] shown in Fig. 1-32(b) is normally based on the combination of elements that give more impedance for the common mode circuit and also create an alternative path for the common mode current bypassing the motor.

Finally, it must be mentioned that there is another way to reduce common mode currents in the electric drive. This alternative way is based on reducing the common mode voltages of the PWM employed. Thus, by reducing the common mode voltage created by the converter, the common mode currents are inherently reduced. Thus, there are several alternative modulation methods oriented to this purpose, and they can be found in specialized literature. In general, they are based on space vector and pulse-width modulation methods [1].

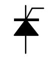
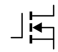
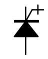
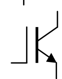
1.4 Classification of different parts of electric drives: converter, machines, control strategies, and energy sources

This section provides a brief perspective of the main elements that can be found in electric drives. Converters, machines, control strategies, and energy sources are briefly introduced. They can be considered the basic electric and electronic technologies employed in electric drives for traction applications or devices.

1.4.1 Converters

By means of controlled and/or uncontrolled switches, such as IGBTs and diodes, we can build up power electronic converters. Such devices can convert voltage from DC to AC or from AC to DC. This subsection enumerates some representative types of converters commonly used nowadays. But, first, some of the commonly employed semiconductors are introduced as well. Table 1-2 shows some of these semiconductor devices. The evolution of power converters and their characteristics is closely related to the evolution of semiconductor devices. In specialized literature, for instance [1]–[4], it is possible to obtain information about the properties of each device and its major characteristics and performance. It can be said it is possible to find in the market semiconductor devices of different rated voltage, current, and many other characteristics, suitable therefore for converters of different characteristics. Thus, probably the most commonly employed semiconductor device is the diode, which is widely used for uncontrolled rectifiers and for controlled power converters. Then there is the thyristor—also known as a silicon-controlled rectifier (SCR). It is line commutated and the

Table 1-2 *Semiconductor devices [1]–[5]*

Diode	
Thyristor	
MOSFET	
GTO	
IGCT	
IGBT	

turn on can be controlled by applying a positive gate current. On the other hand, the turn off depends on the load current so it cannot be directly controlled as the turn on.

The MOSFET (metal-oxide semiconductor field-effect transistor) is a voltage-controlled device. It presents controlled turn on and turn off capability. This device is very popular in low-voltage and low-power applications, because it is possible to operate it at hundreds of kHz switching, causing relatively low switching losses.

On the other hand, the gate turn-off (GTO) thyristor is a self-commutated variant of the thyristor. It can be turned off by a negative gate current, but it is a bulky and expensive turn-off snubber circuit with high snubber losses and a complex gate driver. It was very popular in high-power converters, but nowadays GTOs are not used as much as the four applications described in this book.

It is possible to say that the gate-commutated thyristor (GCT) or the integrated gate-commutated thyristor (IGCT) is the successor of the GTO. Thanks to its constructive nature, it presents lower on-state losses. This semiconductor device presents some variants, such as the symmetric gate-commutated thyristor (SGCT) typically used in CSCs.

The insulated-gate bipolar transistor (IGBT) is probably the most employed device in low-voltage and low-power converters but is also much used in high-power converters. It is a voltage-controlled self-commutated device, with a simple gate driver, snubberless operation, and high switching speed.

Now that we have introduced the most commonly used semiconductors, in the following we briefly introduce the most representative power electronic converters employed in electric drives. As depicted in Table 1-3, although there exist many other types of converters, we can say that the most used ones can be divided into three main groups: rectifiers with diodes (or thyristors, but these are not so much used nowadays), AC/DC or DC/AC controlled VSCs, and DC/DC converters.

Hence, most of these converters have already been introduced in previous sections. The machine of the electric drive is supplied by a DC/AC converter that, depending on the characteristics of the application, can be a two-level converter or a multilevel converter. For high-power applications mainly, there are many possible multilevel converter configurations, such as 3L-NPC, 4L-FC, 5L-ANPC. that are shown in previous subsections. In addition, Fig. 1-33 also illustrates some other examples of stacked multi-cell converter topologies, nowadays not commonly employed in commercial drives but they may be employed in the future.

On the other hand, Fig. 1-34 illustrates some examples of commercially available power converters. Finally, diode-based rectifiers and DC/DC converters are also typically found in electric drives. Here also, there is a wide variety of converters, with different characteristics and performances. Examples of them are provided in subsequent chapters, closely related to the applications in which they are typically used.

Table 1-3 Power electronic converters

Type	Example
Diode or thyristor bridges or rectifiers	6 pulses 12 pulses 18 pulses 24 pulses
AC/DC or DC/AC Controlled VSCs	Two level converter Multilevel converter • 3 L-NPC • 4 L-FC • 5 L-ANPC
DC/DC converters (including or not galvanic isolation)	Flyback Forward Push/pull Dual-active bridge

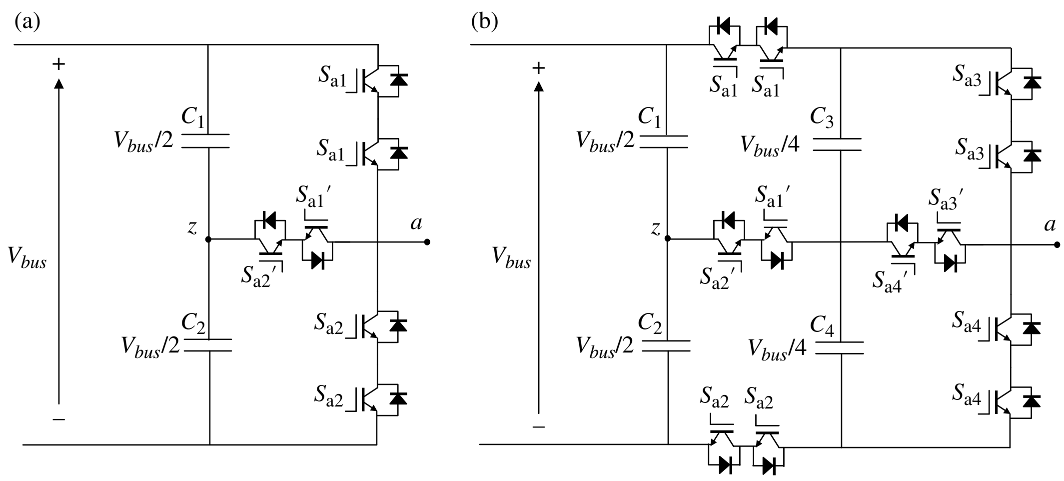


Fig. 1-33 *Stacked multi-cell (SMC) topologies: (a) 3L-SMC, also known as 3L-NPP (neutral point piloted), and (b) 5L-SMC*

1.4.2 Machines

With regards to the AC machines, Table 1-4 shows a simplified classification of machines that can be found in AC electric drives. There are many other type of AC machines; however, this table shows the most representative and used ones in common electric drives. As can be seen, electric machines can be classified into three main groups: induction machines, synchronous machines, and variable reluctance machines. In all these cases, probably the most employed ones are rotating machines with three phases, but it is also possible to find linear

(a) (b)

Fig. 1-34 Examples of commercially available power electronic converters: (a) industry application, MV700: five-level H-bridge neutral point clamped (5 L HNPC) (Source: Ingeteam. Reproduced with permission of Ingeteam) and (b) train application 700 kW/16.5 kV AC Power Converter Box (Source: CAF P&A. Reproduced with permission of CAF P&A)

Table 1-4 *AC machines*

Type	Example
Induction machines (rotating or linear and three-phase or multiphase)	Cage rotor (asynchronous machines) Wound rotor (WRIM) or doubly fed

Synchronous machines (rotating or linear and three-phase or multiphase)	Wound field (WFSM)
	Synchronous reluctance (SyRM)
	Permanent magnet (PM)
	• Axial
	• Transversal
	• Radial
	  ○ Interior
	  ○ Surface
	    ▪ Trapezoidal (brushless DC, BLDC)
	    ▪ Sinusoidal

Variable reluctance machines (rotating or linear and three-phase or multiphase)	Switched reluctance Stepper

machines and also multiphase machines (i.e. those with more than three phases) in both versions (i.e. rotating and linear).

In general, variable reluctance machines are associated with low-power, low-performance applications. This family of machines is cheap and easier to manufacture than the other two groups—induction machines and synchronous machines. In addition, variable reluctance machines require a special converter topology. They are not very common in the applications that are studied in this book, and so are not discussed in any great depth here. On the contrary, the typical AC machines employed in ships, elevators, railway traction, and hybrid and electric vehicles are the induction and synchronous machines. They are constructed in both low-power and

(a) (b)

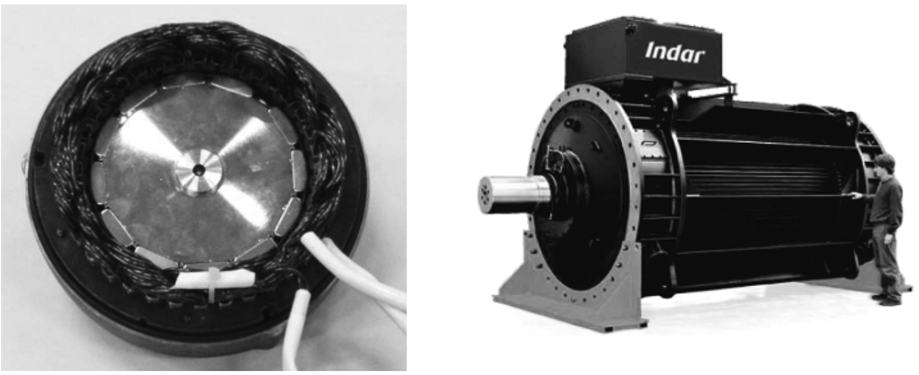


Fig. 1-35 *Machine examples: (a) surface permanent magnet radial synchronous motor for small wind turbines and (b) submersible induction motor for dredge applications (Source: Ingeteam. Reproduced with permission of Ingeteam)*

high-power versions, or in low-voltage or medium-voltage, depending on the needs of the application. In most of their versions, they operate with sinusoidal voltages and currents. Only the brushless DC machine requires non-sinusoidal voltages and currents for the proper operation. The most typical induction machine is the cage rotor induction machine, or asynchronous machine. It is employed in many applications, and the obtained designs are relatively simple and robust. On the other hand, the wound rotor induction machine (WRIM) or doubly fed induction machine is also quite popular. It must be supplied through the rotor and the stator and it is typically employed in wind turbines among other applications.

Finally, with synchronous machines it is possible to obtain a wide spectrum of machine types. Table 1-4 only shows what can be considered the most representative ones. Nowadays, the designs with permanent magnets in the rotor, creating a fixed rotor flux, are very popular. Depending on the direction in which the flux at the rotor is created by the magnets, they can be axial, transversal, or radial synchronous machines. At the time of writing, the most employed design is the radial one. Depending on how the magnets are located at the rotor, they can be interior or surface permanent magnet synchronous machines (PMSM). Finally, depending also on the nature of the stator windings, the machine must be supplied with trapezoidal or sinusoidal voltages. Probably the most employed synchronous machines are radial sinusoidal machines with interior or surface permanent magnets. Fig. 1-35 illustrates some of the above-mentioned machines.

In Chapters 2 and 3, the model and the control of these two machines are analyzed in detail.

1.4.3 Control strategies

This subsection introduces briefly some of the most commonly employed control strategies or philosophies for AC machines. As has been described already, the AC machine of an electric drive must be supplied by the power electronic converter and is typically controlled by a control strategy. Since the beginning of the development of control techniques for AC machines in the early 1970s, many controls have been created. Some of them are based on very simple control approaches; other (extreme) cases are based on really sophisticated control algorithms. This subsection does not intend to classify all existing control strategies. Instead, it offers a simplified view of the most typically employed control strategies for most applications associated with commercially available products or devices. Thus, although it is possible to find a great many control techniques in specialized literature, only a few are mentioned here. Hence, Table 1-5 illustrates a simplified classification of

Table 1-5 *Variable frequency control for AC machines*

Type	Designation
Scalar-based control	V/F control
Vector-based control	Field-oriented
	• Rotor flux oriented vector control
	○ Direct
	○ Indirect
	• Stator flux oriented vector control
	○ Direct
	○ Indirect
	• Airgap flux oriented vector control
	○ Direct
	○ Indirect
	Direct torque control (or direct power control)
	• Direct torque space vector modulation
	• Circle flux trajectory
	○ Constant switching variable hysteresis
	○ Constant switching predictive
	• Hexagon flux trajectory
	Predictive control

variable frequency controls for AC machines. This classification is divided into two groups: scalar-based control and vector-based control. The scalar-based control, in essence, is a very simple and easy-to-implement control philosophy. It does not provide very sophisticated performances in terms of control accuracy, dynamic response, and so on. It was used much more when the control hardware platforms were not as developed as they today and implementation simplicity was a big issue. However, nowadays, thanks to the advance of the control hardware devices such as digital signal processors (DSPs) or microprocessors, vector-based controls are most often used, since it is possible to obtain better control performances with them. Nevertheless, in those applications where simplicity and cost is of great importance, scalar-based control can still be a useful option.

Vector-based control strategies are nowadays the most extensively used ones in electric drives that can be found in commercially available devices or applications. Some of these vector-based control techniques are studied in some depth in Chapters 2 and 3 as they are applied to the control of induction and synchronous machines respectively. Vector-based control techniques, as their name suggests, are based on space vector representation of the most important variables of the machine that is being controlled, such as: voltages, currents, and fluxes. More details about the basic mathematical principles of these controls is provided later. As can be seen in Table 1-5, the first vector-based control categorized group is field-oriented control. Depending on the flux that is utilized as reference for the space vector representation, we can develop rotor, stator, or airgap flux oriented vector control. Additionally, these vector controls can be of direct philosophy and indirect philosophy. In essence, all of these combinations of control techniques provide good performance, but later we will see that probably the most equilibrated and reliable one is the indirect rotor flux oriented vector control, which is probably the one most extensively used by drive manufacturers. Then there is also the direct torque control (or direct power control) philosophy. Within this philosophy, there are also many variants, but Table 1-5 only covers the most popular ones. Direct torque space vector modulation can be said to be very similar to classic vector controls (mentioned earlier), but the main difference is that current loops are omitted. On the other hand, direct torque control with circle flux trajectory is characterized by an absence of modulation, since the pulses for the controlled switches are directly generated by the control itself. This type of control provides very quick dynamic responses, but one drawback, is that they do not make the converter's switches, nor the machine, operate at a constant switching frequency. This has meant that several different control variants that enable one to operate at a constant or near constant switching frequency, such as the variable hysteresis or predictive direct torque controls, have been developed. In addition, hexagon flux trajectory direct torque—better known as direct self-control (DSC)—is another variant of this control family that is traditionally employed in railway traction applications, where the number of commutations of the switches of the converter is limited.

With regards to the modulation techniques which must be employed in communion with the control strategy itself, in order to create the pulses for the controlled switches, as illustrated in Fig. 1-11, it can be affirmed that there exist two main alternative modulation techniques: pulse-width modulation (PWM) and space vector modulation (SVM). Each family of modulation presents different variants and alternatives as well. In specialized literature [1]–[4] and also briefly in subsequent chapters, it is possible to find reach descriptions of such modulations. Nevertheless, it can be said that SVM may be more employed in electric drives, since in general it can obtain better performance with them and be more versatile or adaptable to the needs of the application compared with PWM.

Finally, it is possible to highlight a newer tendency of control philosophies, known as predictive control. By taking advantage of the computational power capacity of newer control hardware devices, this is a more sophisticated control philosophy firmly based on the model of the machine, which achieves the control of the most important magnitudes based on predictions rather than on classic automatic control. Since often this predictive control philosophy is based on space vector representation of the machine, it has been classified as a vector-based control technique.

1.4.4 AC and DC voltage sources

To conclude, this subsection shows some examples of AC and DC voltage sources employed for supplying electric drives. Table 1-6 shows a classification of the most representative voltage sources. For most of the applications, the typical AC voltage source is the electric AC grid, also known as AC utility or AC network. Nowadays, it is created from a combination of AC generator (fixed-speed wind turbines, electric power plants, etc.) and converter-based generation (photovoltaic, thermo-solar, full scale converter based wind turbines, etc.). Depending on the country can reach at the user at different voltage levels and different frequencies.

On the other hand, for railway traction a different voltage source is normally employed which is typically created from the AC grid. To these dedicated voltage sources the name "catenary" is typically used. It is possible to find DC catenaries and AC catenaries of different voltage levels and different frequencies, as is shown in Chapter 5, dedicated to railway traction. In addition, for instance, in hybrid electric vehicles or ships, an alternative AC voltage source is created by one or several AC generators driven by diesel engines. Finally, typically found DC voltage sources are, as mentioned earlier, DC catenaries in railway traction applications and batteries in applications such as electric vehicles.

Table 1-6 *AC and DC voltage sources*

Source	Type
AC	Electric AC grid
	Catenaries for railway traction
	AC generators
DC	Batteries
	Catenaries for railway traction
	Super-capacitors

1.5 Future challenges for electric drives

This section gives a general, and very simplified, view of the challenges facing electric drives and their continued evolution.

As can be deduced from the previous sections, the electric drive technology employed in many traction applications or devices, from an electronic and electric point of view, depends mainly on the evolution of four basic technologies:

- Electric sources: DC (batteries, super-capacitors, etc.) and AC (generators, utility grids, etc.)
- Power electronic converters: rectifiers, inverters, multilevel conversion, etc.
- Electric machines: synchronous, asynchronous, etc.
- Control algorithms or control strategies: vector control, energy management, etc.

Table 1-7 depicts a particular view of the general future challenges of electric drives used in different applications or devices. This table seeks to clarify how the above-mentioned basic technologies should evolve in order to adapt the electric drives' development to the needs and demands of users or society in general. As

Table 1-7 General future challenges of electric drives used in different applications or devices

Challenge	Example
Improving performance	Faster dynamics or more adapted to the user's needs Improve reliability Reduce energy consumption Improve efficiency Reduce volume, weight, dimensions, etc. Improve comfort: Reduce noise and vibrations, improve acceleration and braking, jerk, etc. Increase the life of the equipment. Reduce maintenance
Adapting to different operating conditions or demands of the specify of the application (versatility)	Be able to adapt to different needs of power, speeds, voltages, energies, etc. Be able to move heavier loads and faster in trains for instance Improve the autonomy of electric vehicles for instance Elevators at higher buildings moving heavier loads Trams that can operate without catenary in longer periods Approach to the port of ships only moved by batteries reducing the noise.
Reducing costs	Cheaper elements or parts Cheaper manufacturing processes Faster production times
Being more environmentally friendly	Reduce emissions Save energy Reduce noise Avoid using polluting materials or polluting manufacturing processes Avoid damage to animals and plants and Nature in general
Improve working conditions of people involved in doing the electric drives and devices' different parts	Avoid hard/dangerous/stressing working conditions of workers Increase: Motivation, identification with challenges, etc.

Table 1-8 *A simplified classification of materials employed in electric drives*

Types	Examples
Semiconductors and microprocessors	Silicon Cupper: base plates Silver: union between chips, cold plates Aluminum oxide (Al_2O_3): isolation between silicon and base plate
Electric machines and inductances for filters	Magnetic cores: silicon steel (for magnetic sheets), soft magnetic materials in small machines Electric circuits: copper and aluminum for coils and squirrel cages Housing and end-caps: aluminum, iron (cast) Steel for shafts Materials for electrical insulation: epoxy, varnish, Nomex 410, plastic, polyimide, polyethylene Magnets: rare earths and ferrites
Batteries	Lead acid: Pb, H_2SO_4, H_2O_2 Nickel cadmium: nickel oxide-hydroxide, cadmium, alkaline electrolyte Nickel-metal hydride: nickel hydroxide $Ni(OH)_2$, cadmium, KOH electrolyte LiOn: lithium cobalt dioxide ($LiCoO_2$), Lithium manganese oxide spinel ($LiMn_2O_4$) Lithium-nickel cobalt manganese Polypropylene for cases Cathode chemistries: $LiNiCoAlO_2$, $LiNiMnCoO_2$, $LiMn_2O_4$, $LiFePO_4$ Anode materials: graphite (natural or synthetic), soft or hard carbon
Ultracapacitors	Carbon, aluminum, organic electrolyte
Other electronic elements	Plastic capacitors: polypropylene, polyethylene, aluminum Ceramic capacitors Transformers: same materials as electric machines and epoxy (dry transformers), mineral oil, ceramics

summarized, the electric drives for tractions applications should try to improve aspects such as: performance, adapting to different operating conditions, being more environmentally friendly, reducing costs, and improving working conditions. To these ends, the specific development of the basic technologies (converters, machines, controls, and supply sources) should involve trying to meet these general challenges. Later chapters look at the specific needs of four specific applications in turn.

Section 1.5 is intended to be a general, and simplified, approach to future challenges.

Finally, the above-mentioned basic technologies for electric drives are made of different materials. Thus, Table 1-8 shows in a simplified manner an enumeration of the materials employed in electric drives and so gives a view of the basic materials needed to create the different elements or parts of an electric drive.

1.6 Historical evolution

Briefly, this section shows some of the most remarkable achievements or developments in electric drive multidisciplinary technology. There have been many advances in the history of electric drives that cannot be included in this section. Instead, a short representative classification of technological inventions and developments is provided in Table 1-9.

Table 1-9 *A summary of the most notable events in the evolution of electric drive technology [6]–[7]*

1837	Davenport patents the DC motor. Some few years earlier, Jacobi, Strating, and Becker also developed several equivalent DC motors and many other inventors also developed more primitive electric motors or electromagnetic arrangements
1859	Gaston Planté invents the first lead acid battery
1882	Development of the New York City DC distribution system by Edison
1882	Jasmin discovers the phenomenon of semi-conductance and proposes its use in AC rectifying
1885	Ferraris develops the rotating magnetic field by polyphase stator windings
1887–1888	Haselwander builds the first three-phase synchronous generator with salient poles
1888	Tesla develops the commercial wound rotor induction motor
1889–1891	Dobrovolsky develops the cage induction motor
1891	Tesla develops the polyphase alternator and Dobrovolsky develops the first three-phase generator and transformer creating the first complete AC three-phase system
1892	Arons develops the first mercury-arc vacuum valve
1897	Graetz develops the three-phase diode bridge rectifier
1899	Jungner invents the first rechargeable nickel–cadmium battery
1902	Hewitt patents the mercury-arc rectifier
1906	Pickard proposes the silicon valve
1929	Park defines the synchronous machine d–q analytical model in synchronous reference frame
1938	Stanley defines the induction motor model in stationary reference frame
1948	Bipolar transistor is invented by Bardeen, Brattain, and Shockley generating an electronic revolution
1952	General Electric manufactures the first germanium diodes
1954	Texas Instruments produces a silicon transistor with high commercial acceptance
1956	Moll, Tanenbaum, Goldey, and Holonyak invents the thyristor, starting the first era of power devices development
1963	Turnbull develops the selective harmonic elimination PWM
1964	Schonung and Stemmler develop the sinusoidal PWM
1968–1972	Hasse and Blaschke pioneer the indirect vector control and direct vector control
1971–1972	Intel introduces the firsts 4-bit and 8-bit microprocessors
1979	Plunkett publishes the hysteresis band PWM for the AC motor drive
1981	Nabae, Takahashi, and Akagi first publish the three-level neutral diode clamped converter
1982	Pfaff, Weschta, and Wick propose the space vector PWM, which is later developed by Van der Broeck, Skudelny, and Stanke
1983	General Electric invents the insulated-gate bipolar transistor (IGBT)
1984–1986	Depenbrock on the one side and Takahashi and Noguchi on the other develop the direct self-control technique and direct torque control technique
1990	Following the development of Ni-Mh (nickel metal hydride) batteries in the second half of the 20th century, the commercialization starts
1991	Sony commercializes the first lithium-based rechargeable battery, improving the technical specifications of the rest of technologies significantly
1997	ABB introduces the insulated-gate controlled thyristors (IGCT)
1990–2000	Introduction of voltage source converter (VSC) drives in many applications and devices
2000–2016	Introduction of permanent magnet-based motors. Introduction of battery-based energy storage systems in many applications
	New semiconductor technologies

References

[1] Abu-Rub H, Malinowski M, Al-Haddad K. *Power Electronics for Renewable Energy Systems, Transportation and Industrial Application*, Chichester: John Wiley & Sons, 2014.

[2] Bose BK. *Power Electronics and Drives*, London: Elsevier, 2006.

[3] Wu B. *High Power Converters and AC Drives*, Piscataway, NJ: IEEE Press, 2006.

[4] Mohan N, Undeland T, Robbins R. *Power Electronics*, New York: Wiley InterScience, 1989.

[5] Kouro S, Rodríguez J, Wu BS, et al. Powering the future of industry: High power adjustable speed drive topologies. *IEEE Industry Applications Magazine* August 2012.

[6] Bose B. Doing research in power electronics. *Industrial Electronics Magazine* March 2015, 1.

[7] Various Wikipedia articles.