## Edited by GONZALO ABAD

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**GONZALO ABAD** Mondragon University, Spain

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### Preface

The work presented in this book offers a practical approach to electric drives. Electric drives are in charge of controlling the movement of devices or appliances that we can find in our daily lives, such as air conditioning systems, washing machines, trains, trams, ships, electric vehicles, hybrid vehicles, elevators, ventilation systems, and wind generators. Thus, the electric drive is part of the electromechanical equipment that enables, for instance, the driver of an electric vehicle to accelerate, decelerate, and maintain a constant speed—ultimately, to drive the car. In a similar way, the electric drive enables an elevator to move from one floor to another as required by its users, while maintaining certain standards of comfort, safety, efficiency, and so on.

This book describes in detail electric drives used in the following extensively used elements and devices: trains, ships, electric and hybrid vehicles, and elevators. In all these elements, and in many others, the electric drive is designed to be able to produce a controlled movement in accordance with the needs and preferences of the user. In essence, the basic electric and electronic working principles and fundamentals of the electric drive for each device are the same. However, for an optimized, safe, efficient, reliable, and comfortable. Performance, the basic fundamental electric drive concept must be adapted to each application or device.

Thus, in this book, the various characteristics of electric drives employed in the above-mentioned applications are described, providing details of how the device itself, with its needs, defines the characteristics of the electric drive. This means, for instance, that the electric drive of a train must be prepared to receive energy from the catenary, transform this electric energy into a controlled movement of the wheels that move the wagon, being able to travel to the different speeds and accelerations required by the driver, and avoiding undesirable and dangerous slipping of the traction wheels so typical in trains.

Structurally, the electric drive is composed of three basic technologies. First, electric machine technology is an important part of the electric drive. The electric machine converts electrical energy into mechanical energy employed to move something. For instance, in an elevator, the electric motor moves the drive sheave. At the same time, this drive sheave moves ropes attached to the car to ferry passengers from floor to floor. In a similar way, the movement of a ship is carried out by the propeller, and the electric machine is in charge of generating the rotatory movement of the blades of the propeller at different speeds. Equally, in road vehicles and trains, the electric motor is in charge of controlling the rotatory movement of the driving wheels.

The power electronic converter technology is in the electric drive. The power electronic converter supplies the electric machine with the necessary electric energy, taken from the energy source. For instance, in an electric vehicle, a power electronic converter supplies the electric motor with energy, typically in AC form, converted from the batteries (the energy source) in DC form.

Third, a control strategy or control algorithm is also necessary in the electric drive. There exist different control philosophies or technologies in electric drives. The strategy controls the movement of the electric motor by sending the necessary orders to the power electronic converter, responding to the demands of the

user. For instance, in a ship, the control algorithm, following a demand from the user to travel at a certain speed, controls the speed of the electric machine at a constant speed, which also moves the blades of the propeller. To this end, it sends the appropriate orders to the power electronic converter to provide the required energy to the electric machine. Note that the control must be able to employ the required energy from the energy source, no matter how much the wind is in opposition to the ship or the load it carries, or how rough or calm the sea is.

There is another element that has already been mentioned, which is the energy source. Sometimes, the electric source can be considered a part of the drive itself. This element obviously influences the design and construction of the electric drive and consequently the performance of the ship, train, elevator, and so on. For instance, in electric vehicles, the most commonly employed energy sources are batteries. Depending on the nature and characteristics of these batteries, the electric drive must be accordingly adapted, which is an important part of the global design of the drive.

To use an analogy, the propeller of a ship is like a person's legs. The electric machine in charge of rotating the propeller to move the ship could be the heart and the nervous system. These organs provide blood and nervous stimulus to move the muscles of the legs, thus the energy source of the ship, which is often a combination of diesel engines and batteries, in the person would be the food, water, air, and so on. needed to be able to walk. The power electronic converter that converts the energy in a ship from batteries and diesel engines into electric energy for supplying the electric machine in a human could be the digestive and respiratory systems. Finally, the control system in a ship sends orders to the power electronic converter, to produce movement at the machine and therefore at the propeller. In a human the control could be the brain, which is in charge, among other things, of sending orders to the nervous system to move the legs by means of its muscles. Also, of course, there are many other technologies in electric drives which have not been highlighted, for instance, measurers or sensors of speeds, currents, voltages, etc. necessary for control. In humans, we have, for instance, a vision system, auditory system, olfactory system, etc. which are needed to send information from images, sounds, and smells to the brain to be processed.

Obviously, this comparison, like all analogies, is not perfect, but it gives an idea of the romantic parallelism between humans or animals on the one hand and devices such as vehicles, ships, elevators, and so on, which are created by humans, on the other. It is clear that animals are much more complex than the technology created by humans. Animals and humans are the result of many millions of years of evolution. However, humans started creating technology, according to some anthropologists, only around two or three millions years ago, when one of our "grandfathers", an early hominid, discovered that braking a boulder with another boulder creates broken boulders with an edge, which is a kind of device that allowed early humans to cut meat. From that moment on, technology created by humans has evolved to very sophisticated elements of equipment, such as elevators, vehicles, ships, airplanes, robots, smartphones, rockets; unimaginable to those ancient humans.

Over millions of years, life, whether it be plant or animal, has evolved to adapt to an ever-changing environment. In parallel, technology created by humans is also evolving, trying to adapt to the ever-changing needs of humans. For instance, many concepts employed in shipbuilding that once were useful, even innovatory, have passed by the way, to be replaced by the modern, electrically propelled ship. In a very similar way, many species of animals have disappeared or become extinct, but they were the base or root of the species of animals today. In a similar way, in Nature we can find diversification of life, for instance falcons that can fly very fast and have developed incredibly strong eyesight share the skies with ducks that can walk and swim over the water as well as fly. And so, for instance, with trains: there are trains that specialize in travelling at high speed over long distances, others in carrying heavy and bulky loads, and yet others in travelling at low speeds through the cities, in some cases even disconnected from the catenary or energy source and travelling with the help of batteries. Moreover, there exist some types of trains which do not employ catenary or external energy sources but take their required energy from an engine that is located within the train. These types of trains are, essentially, moved by a tractive electric concept that is very similar to those employed in hybrid-electric vehicles that travel on roads with tires. Thus, this could be understood as an adaptive approach of trains to road vehicles. In Nature, we can also find many equivalent approaches. For example, the dolphin is a mammal with the bones, digestive system, respiratory system, limbic system, social habits, and so on that are very similar to other mammals—such as humans, cows, pigs, and horses—but whose adaptation to its marine environment, and specifically its hydrodynamic requirements, has made it externally in appearance like other fishes, for instance sharks. In a similar way, bats are probably the only mammals that fly, having adapted their forelimbs to wings. Also, having the dense bones of mammals compared to those of birds, they require a huge amount of energy to sustain their flight, and so they need to eat a great many insects in relation to their weight.

In this way, it can be said that human technological developments, which evolve to survive the changing needs of societies, are living entities which adapt to the environment, adopting many different strategies. Just as flowers need to attract bees to aid their pollination and, therefore, their reproduction, elevators created by humans must be attractive to other humans in order to maintain the demand for them so that they will be produced again and, consequently, evolve. Note that it is common that humans adapt themselves to new technological advances rather than advances to humans. Look, for instance, at the Internet, social networks, smartphones, and so on. These have changed the habits and behaviors of humans.

Hence, these "living" technologies, or advances, created in multinational companies, industries, research centers or university departments, and so on, compete with each other and so, in a way, are trying to survive. However, not only the technology created by humans is evolving on the basis of competition, because in parallel and just as interconnected, all the abstract concepts created by humans are also competing to survive: nations, countries, tribes, races, individual careers, clans, societies, religions, ideologies, lobbies, empires, kingdoms, economic concepts, financial interests, forms of economies, forms of consumerism, entertainment industries, and so on.

In this way, it is obvious that over thousands of years, by repeating the same behavioral patterns, humans accumulate abstract images, concepts, or ideas, which are also living entities, evolving and competing to survive. Unfortunately, the history of human civilization shows that competition brings conflict. Inevitably, these concepts create an enormous disorder on earth, with a tremendous accumulated inertia, which unfortunately also creates too much physical violence, non-physical violence, conflicts, suffering, antagonisms, hate, jeal-ousy, overpopulation, sorrow, irrational actions, and so on. on all living entities of earth, including its climate, atmosphere, seas and oceans, mountains, animals, plants, societies, technology, religions, and so on. We do not know whether animals, for instance, can perceive this disorder; humans can, however. These are facts. With these concepts, humans seek security, but we have created division and therefore suffering because the division tries to survive. The burden of these concepts dominates humans' thinking, their relationships, and their daily life. Often, we are so consumed by and accustomed and conditioned to the conflict caused by these concepts that we do not even perceive it and, therefore, do not realize how dangerous it is for the planet, which is a unique living entity of which humans are only a part.

Obviously, it is true that we can also find positive and harmonious evolution, but it is probably too slow and comes at a great cost. Human beings call themselves *Homo sapiens*, but it is not clear whether we behave according to the meaning of that second word, *sapiens* (wise). Unfortunately, neither is it clear how long this behavior can be sustained and whether the planet will be able to resist this tremendous division and disorder that we have created for millennia. As another analogy, again, we can say that humans are now behaving like an uncontrolled plague. Even laboratory experiments with mice, which are mammals, just like humans, have shown that when they obtain food by moving a lever but at the same time see that another mouse receives an electric discharge, they choose not to eat. They prefer not to see another member of their species suffer rather than satisfy their hunger. Humans must recognize this situation and get their own house in order before it is too late. This is probably our greatest global challenge.

Everything written in this book—from this preface to the equations, algorithms, analyses, diagrams—has been inspired by works created with or by others. We just gave a certain structure to contributions of many individuals, many groups, and many multidisciplinary teams. We would like to acknowledge these many and uncountable people who contributed to the concepts contained in this book. In conclusion, we hope that this book will be of interest to and useful for the reader.

Gonzalo Abad Mondragon University, Spain June 2016

### 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.

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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.



(b)



*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)

Industry applications	Mining: • Conveyors • Grinding mills • Crushers • Shovels • Water pumps • Ventilation fans • Hoists
	<ul> <li>Petrochemical:</li> <li>Oil pumps</li> <li>Gas compressors</li> <li>Water-injection pumps</li> <li>Mixers</li> </ul>
	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
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

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

(continued overleaf)



Table 1-1(continued)



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