Power Electronics and Electric Drives for Traction Applications

Edited by
GONZALO ABAD

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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, jealousy, 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.

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June 2016

Contents

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.

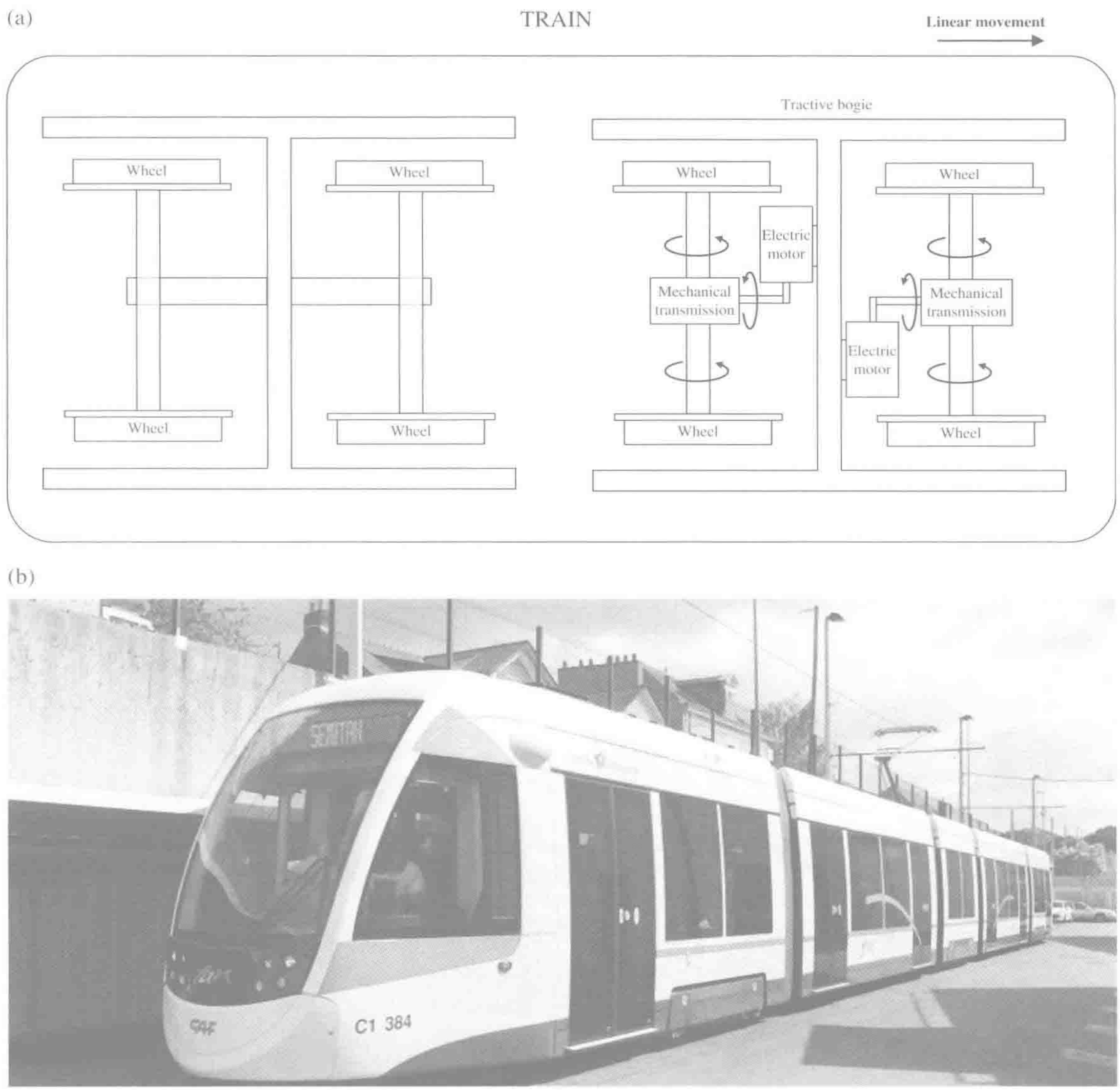

Fig. 1-1 *(a) Schematic representation of the basic movement operation principle of an electric train, (b) Example of a real tram (Source: CAF. Reproduced with permission of CAF)*

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

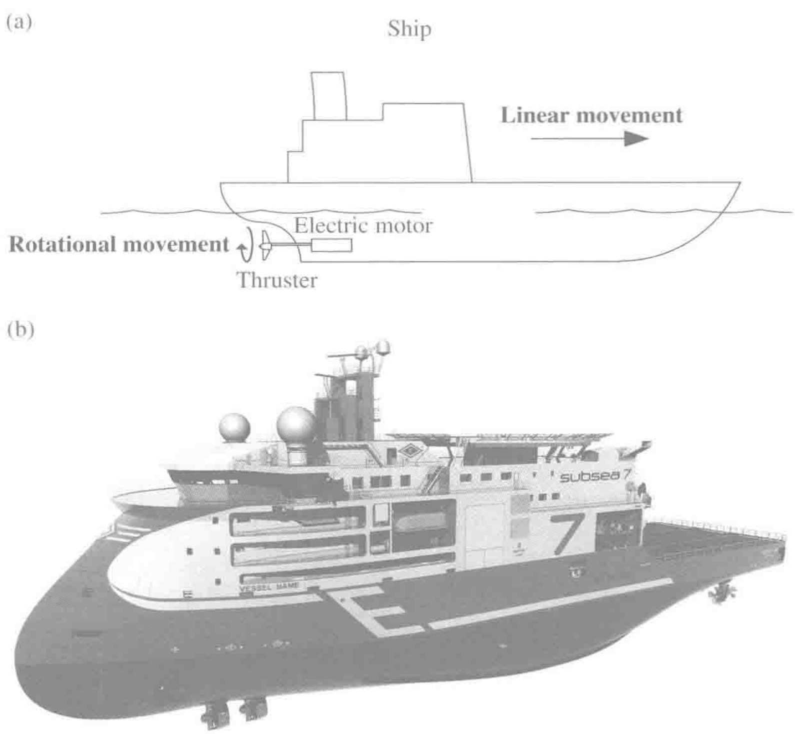

Fig. 1-2 (a) Schematic representation of the basic movement operation principle of a ship, (b) Example of a real ship (Source: Ulstein. Reproduced with permission of Ulstein)

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

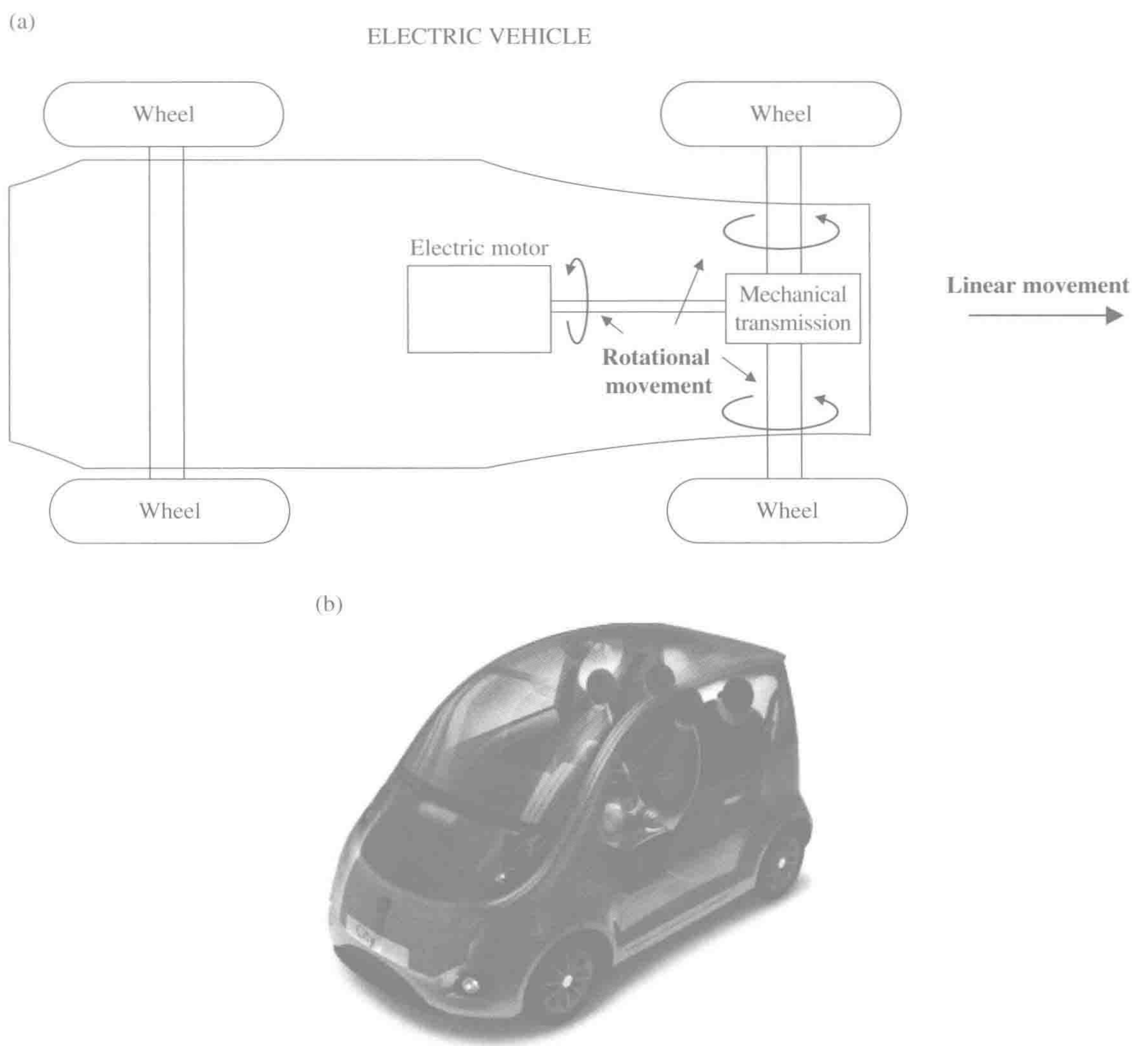

Fig. 1-3 (a) Schematic representation of the basic movement operation principle of an electric car, (b) Example of a prototype of electric car