

RÉPUBLIQUE ALGÉRIENNE DÉMOCRATIQUE ET POPULAIRE  
MINISTÈRE DE L'ENSEIGNEMENT SUPÉRIEUR ET DE LA RECHERCHE SCIENTIFIQUE  
UNIVERSITÉ MOHAMED BOUDIAF- M'SILA

FACULTÉ DE TECHNOLOGIE  
DÉPARTEMENT D'ÉLECTRONIQUE  
N°:.....



DOMAINE: S. ET TECHNOLOGIE  
FILIÈRE: **Électronique**  
OPTION: **Instrumentation**

## MÉMOIRE DE MASTER

Présenté en vue de l'obtention du diplôme de Master Académique

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Intitulé

**Implementation of the DTC technique in a DSP card  
to control an asynchronous motor intended for electric vehicles**

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Année universitaire 2021/2022

**THANKS**

*We thank **Allah** for having given us the will, the health and the patience during all these long years of study.*

*We sincerely thank our supervisor 'Dr. Amar GUICHI' for proposing this theme and directing this modest work and for his continual correction of the memory and the continuous realization throughout the memory, he has given us an excellent example of scientific competence and discipline.*

*We also address our gratitude to all the professors and the administrative staff of the electronics department for their advice and knowledge generously imparted.*

*We would also like to thank the members of the jury for having agreed to review this work.*

*A big thank of love for our parents who gave us the help and the motivations as well as the means that provided and facilitated the realization of this project.*

*To all our friends with whom we spent pleasant moments, for their help and encouragement.*

*Finally, we would like to thank all the people who have contributed directly or indirectly, to the culmination of this work.*

DEDICATION

*I dedicate this work and my successive successes to the most tired and raised human being who suffered a lot in order to see our dreams been true, who always motivates me to achieve more. To my **Beautiful Mother**.*

*To the pure soul of **my father**, as long as I wished that he would see my achievements and be proud of his only daughter. May God have mercy on his soul.*

*To all my teachers from my first year of university to this fifth year.*

*I dedicate this work to the honorable Teacher **GUICHI Amar** , that I had the honor to work with him.*

**MESSAHEL Nour El Houda**

*I dedicate my work to my honorable father **BENDJOUDI Mohemmed**. Thanks to God and thanks to him for helping me to reach this place. May God protect him for me.*

*To my dear mother **DJAOUADA Fatiha**, thanks to her hard work and her prayers.*

*To my sisters and brothers, to my friends.*

*Finally, I would like to thank everyone who supported me in my academic journey.*

*Thanks and appreciation to Professor **GUICHI Amar***

**BEN DJOUDI Nadjoua.**

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## GENERAL INTRODUCTION

An Electric Vehicle (EV) is a mode of transportation powered entirely by electricity, which is stored in a battery pack to move the wheels where one or more electric motors are used.

The electric car projects are mainly developed to change the global climate, particularly by reducing the carbon dioxide emissions. But despite the success of the idea of using electric cars and its continuous development, the big challenge facing these environmentally friendly means of transportation are its high price and the efficiency of the battery and the time of its charging.

Electric cars use single-speed transmission, unlike conventional cars that need multiple gears and the used electric motors can generate torque at very low speeds. Electric car motors are powered by rechargeable lithium-ion batteries, which in testing have successfully recharged 3,000 cycles, meaning that the battery works - in principle - for a total distance of 300,000 km. The current difficulty is the difficulty of increasing the car range above 400 km on a single charge of the battery, and reducing the recharging time, as charging the battery currently takes about 2-3 hours, during which the car does not move.

Electric vehicles are distinguished from those equipped with an internal combustion engine by the type of engine and the source of energy, the EVs engine is an alternative motor powered by the electric energy stored in the battery, therefore, applying the advanced control techniques on the motor will increase the performance of the motor and that of the car as well. For this reason, we proposed to control the speed of the asynchronous motor, the type of motor most used in the EVs, by applying the direct torque control technique (DTC), which will make it possible to impose the speed on the motor whatever the value of the resistive torque.

This work has been started by giving an overview of the working principle of electric vehicles in general, then the theory of the applied speed control technique has been well explained, and then applied to the asynchronous motor. These three important parts of this work have been developed in three chapters as follows.

The first chapter will be devoted to the study and presentation of electric vehicle systems, starting with the presentation of their evolution throughout history, then the devices constituting the propulsion system of these cars, the advantages/disadvantages of these cars, ending by the presentation of the New European Driving Cycle 'NEDC' which will be used to test and confirm the effectiveness and accuracy

of the proposed speed control technique.

In the second chapter, a detailed explanation of the asynchronous motor, its components, its principle of operation and its mathematical equations will be presented and it will end with the presentation of the simulations results of the motor working under variable-frequency supply voltage (Motor + inverter) in the PSIM environment.

In the third chapter, a general overview of different asynchronous motor speed control techniques will be provided, and then the theory of Direct Torque Control (DTC) technique will be detailed. subsequently, this technique will be applied to control the speed of the asynchronous motor intended for the electric vehicle. this will be done first by simulation in the PSIM environment, then the control program will be implemented in the t TMS320F28335 targe of the PSIM and finally, as our experimental setup is not ready, we will validate our program by processor-in-the-loop (PIL) simulation. the simulation results of the three stages will be given and discussed.

## 1.1 Introduction

Electric vehicles (*EV's*) are currently a possible alternative to conventional vehicles, allowing vehicle manufacturers to meet the requirements demanded by vehicle users (performance and fuel consumption) and atmospheric protection laws (reduction of pollutant emissions).

The electric car has often been considered as a technology with a bright future and which gives hope for putting an end to this alarming pollution of the atmosphere due to the road transport sector.

Designed to effectively fight against pollution, electric vehicles are, unfortunately, hampered by their high costs, their limited autonomy which depends on the capacity of the batteries, the lack of investment and other critical problems that handicap this invention.

The idea of the electric vehicle is not recent and yet its internal structure is not fixed. Several solutions are currently in development. Research in the field of batteries is important and gives rise to many prototypes.

In this first chapter, an overview and a brief history of the electric vehicle will be given, then its operating principle as well as its different architectures and constituent elements will be detailed.

## 1.2 Definition

EVs are currently a possible alternative to conventional vehicles, allowing vehicle manufacturers to meet the requirements demanded by vehicle users (performance and fuel consumption) and atmospheric protection laws (reduction of pollutant emissions). The electric propulsion system is the main organ of the EV, it is propelled electrically by motors and comprises a transmission system formed by one or more electric motors driving two-wheel drive. It has a very simple architecture. It consists of an electric actuator, a transmission device, and wheels (Figure 1.1)

## 1.3 History of Electric Vehicles

The word *car* came from the French word *automobil*, which means a machine, meaning that it moves itself rather than being pulled, or pushed by another machine or by another animal. It was formed by

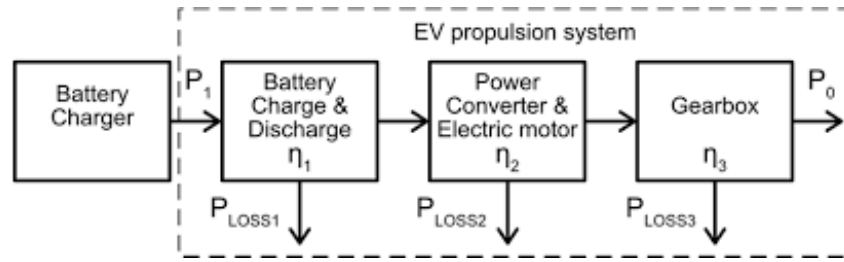


Figure 1.1: EV propulsion system

combining the Latin words *mobilis*, which means: moving, and the Greek word *autos*, which means itself.

Contrary to popular belief, the beginnings of the electric car coincide with those of automobile history, the first was the JEANTAUD in 1894, it was a two-seater phaeton, The electric car existed long before. In 1828, Hungarian priest and physicist Agios Jedlik invented a primitive type of electric motor, and built a small model of a car running on his innovative engine. Between 1832 and 1839, Scottish inventor Robert Anderson also invented a purely electric carriage. In 1835, Professor Cybrandus Strating of Groningen, Holland, and his assistant Christopher Becker of Germany also invented a small electric car, running on non-rechargeable primary cells.

The discoveries of the laws of electromagnetic induction by Michael Faraday in 1831 allowed the development of electric motors. Three years later, the American Thomas Davenport built a small electric locomotive which was the first automobile with non-rechargeable accumulators, the latter managed to travel a short distance on rail, Then in 1838, Robert Davidson added some modifications to it to arrive at a similar model, which can travel up to 6 km/h. These two inventions did not use a rechargeable battery, since the latter was not yet invented, they worked with non-rechargeable batteries.

Rechargeable batteries did not become a viable means of storing electricity on board a vehicle until 1859, with the invention of the lead-acid battery by French physicist Gaston Plante. Camille Alphonse Faure, another French scientist, notably developed the battery design in 1881, His developments greatly increased the capacity of these batteries and directly led to their industrialization.

In November 1881, Gustave presented an electric automobile, or rather an electric tricycle, at the International Electricity Exhibition in Paris. Nevertheless, it was only a prototype and its use was more than delicate, since the conductor had to, thanks to a system of pulleys, immerse metal plates in containers containing acid in order to modulate the intensity of the current and therefore the speed, Around 1897, the first electric taxis began to appear in the streets of New York, then in 1899, in Belgium, a company built ‘La jamais centent’, it was the first electric car to exceed 100 km/h [1].

English inventor Thomas Parker, who was behind inventions such as the electrification of the London Underground, vertical trams in Liverpool and Birmingham, and the smokeless Qualite fuel, built the first production electric car in Wolverhampton in 1884, although the only documentation is a photograph of 1895.

Parker’s long-standing interest in building more efficient and fuel-efficient cars led him to experiment with his electric cars. He may also have been concerned about the harmful effects of smoke and pollution on London. The car was produced by the Elwell-Parker Company, founded in 1882 to build and sell electric trams.

The company merged with other competitors in 1888 to form the Electric Construction Company; This company had a near-monopoly influence on the British electric car market in the 1890s. The company built the first electric *dogcart* (a light cart, usually horse drawn). France and the United Kingdom were the first two countries to support the widespread use of electric vehicles. German engineer Andreas Falken built the first true electric car in 1888.

The first electric car was developed in the United States in 1890-91 by William Morrison of Des Moines, Iowa, The car had a six-passenger vehicle capable of reaching a speed of 23 km/h (14 mph). It wasn't until 1895 that consumers began to dedicate their attention to electric vehicles, after A.L. Riker, the first tricycle in the United States.

Although, in 1900, out of 4,200 vehicles manufactured in the United States, 22 % were gasoline, 38 electric and 40 steam, the poor range performance of electric vehicles in the face of thermals soon put an end to the development of electric vehicles. The latter was then quickly overtaken by thermal engine vehicles at the dawn of the 19th century, because of their too low speed, and their lack of power, thus the technological blockage of the batteries of the time having a poor autonomy, and the rise of oil at unbeatable prices, and with the arrival of the Ford T in 1908 at half the price, the electric vehicle was therefore completely pushed into decline. But nowadays, electric cars are constantly appearing, much more sophisticated and practical, they invade the market more and more, and then begin to become more democratic little by little [1].

The image of Figure 1.2 is the photo of the first electric car to be able to overcome 100 kilometers per hour: the never happy *'la jamais centent'*.



Figure 1.2: *la jamais centent* electric car

The development of the electric vehicle becoming imperative to answer the problem of the pollution of the cities, studies relating to the choice of the chain of traction are carried out by several electrical equipment manufacturers (LEROY SOMER, AUXILEC, ...) as well as by large automobiles groups (NISSAN, GENERAL MOTORS, ...) in order to improve its performance.

Several research programs on electric vehicles have been held recently to declare the coming of this technology soon, due to the rise in oil prices and the emergence of some environmental problems like air pollution in the urban areas, which resulted from the uncontrolled use of the conventional gasoline

engine. However, the electric vehicle seems to be a promising solution to reduce traffic pollution in large cities, because this type of car does not induce atmospheric and noise pollution.

Today, electric cars are focused on urban use. They are often small in size. However, they remain quite expensive, for example Mitsubishi has been marketing an electric car since 2009 in Japan, with respectable performance at a speed of 140km/h according to their announcements [1].



Figure 1.3: Mitsubishi electric car

## 1.4 Components of an electric vehicle and how it works

### 1.4.1 Components of an electric vehicle

The components present in electric cars are never the same depending on the model manufacturer and the technology used. However, some are essential to be able to qualify a motor vehicle as electric.

The electric vehicle comprises a high-voltage battery whose volume and mass are significant (approximately 300 kg). The battery is charged either from cable charging, from an external source, or from vehicle deceleration. The capacity of the batteries is around 5 to 40 kWh, their total voltage if from 300 to 500V.

The car is also equipped with several converters, battery chargers and some accessories as well as one or more electric motors. The use of solar panels in electric vehicles is also possible, the latter allows the battery to be recharged in small quantities, unfortunately this is not always a good help, since the car must be very light, any additional charge would further reduce its performance, not to mention the very high cost [2].

### 1.4.2 Energy sources

Using electricity as a power source to power an electric vehicle motor is a real challenge, concerning the on-board storage of electrical energy for electric vehicles, electrochemical accumulators currently offer the best performance in terms of mass or volume energy. The storage of electrical energy is the major problem of the electric vehicle. In this part, we will briefly present the possible technologies.

### 1.4.2.1 Batteries

The most efficient and promising storage systems consist of batteries or hybrid systems. A battery consists of two or more electrical cells combined in series or parallel strings to achieve the desired voltage and capacity. Cells convert chemical energy into electrical energy. The cells include negative and positive electrodes in an electrolyte.

DC electricity is generated by the chemical reaction between the electrodes and the electrolyte. As with secondary or rechargeable batteries, the chemical reaction can be reversed by reversing the current and the battery is returned to a charged state. The actual battery electric vehicle (BEV) is relatively low in terms of energy density, which can directly influence the EV's maximum all-electric driving distance. The major problem of the latter is the lifespan which is not very long, and the significant time it takes to charge [3].

The range of the vehicle depends on the energy stored in the battery (mass energy of the battery). The new generations of batteries allow greater autonomy, without having to carry excessive quantities of batteries, the following characteristics are expected from a traction battery:

- A good specific power (ratio power/weight in W/kg) allowing important accelerations.
- Good specific energy (Wh/kg) synonymous with good autonomy.
- Stable voltage resulting in regular performance.
- A long lifespan, calculated in number of charge/discharge cycles, leading to a reduction in cost for the user.
- Low maintenance and recyclable.
- Possibility of fast charging

Among many different battery technologies, some batteries can be used on electric vehicles, in particular[4].

**Lead-acid battery:** This technology offers high-speed performance, moderate low and high temperature performance, easy indication of state of charge and good charge retention for intermittent charging applications. There are few disadvantages like: low energy density and long charging time, heavy and it needs careful maintenance [4].

**Nickel-cadmium (NiCd) battery:** It was used in the beginning of space exploration. It has a long cycle life, good low temperature, and can be fully discharged without damage. As disadvantages, it is expensive, as cadmium is very toxic, the use of these batteries in EVs is therefore prohibited.

**Nickel-metal hydride (NiMH) battery:** These cells have a higher capacity than nickel-cadmium cells, fast recharging capability, long life and long shelf life. The disadvantages of this technology are that it has low charging and discharging efficiency, high cost, poor cold weather performance.

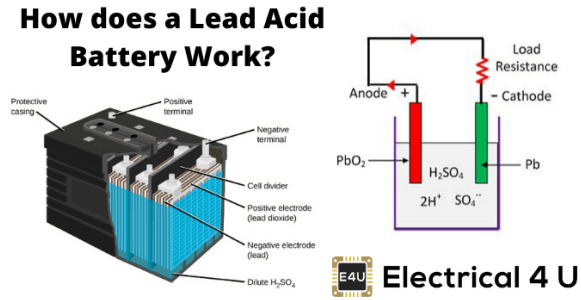


Figure 1.4: Lead-acid battery



Figure 1.5: Nickel-cadmium (NiCd) battery



Figure 1.6: Nickel-metal hydride (NiMH) battery

**Sodium-nickel chloride battery:** Some advantages of these batteries are their relatively high energy density of 90-120 Wh/kg, as well as their insensitivity to ambient temperature. However, the main disadvantage of these batteries is that they need to be recharged when not in use so they are also inefficient as they consume power even when not in use.

**Lithium-Ion (Li-ion) battery:** Li-ion batteries are characterized by their energy density, which allows the vehicle to have a longer electric range; however, they generally do not have the specific power to deliver or accept large power spikes. They are used mainly in the latest electric vehicles nowadays.

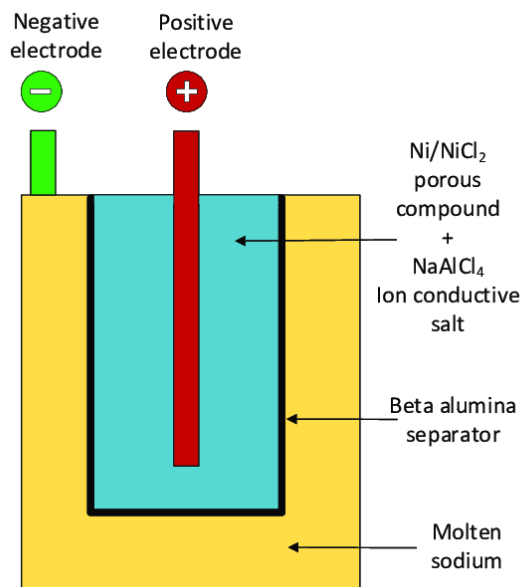


Figure 1.7: Sodium-nickel chloride battery

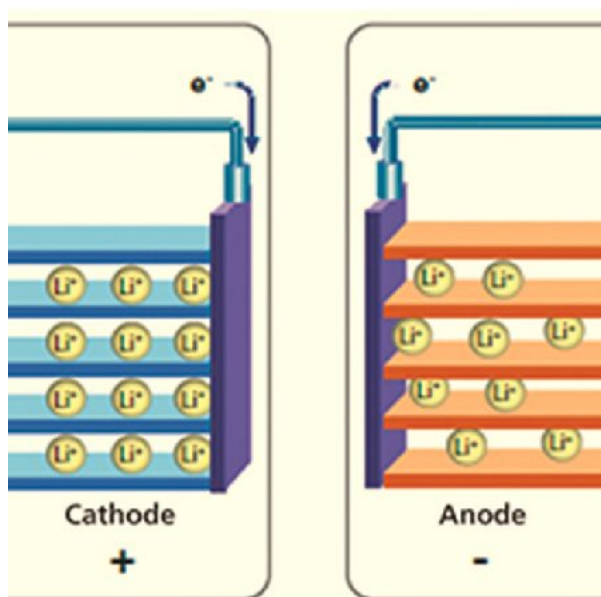


Figure 1.8: Lithium-Ion (Li-ion) battery

#### 1.4.2.2 Fuel cells

The fuel cell can be another source of energy for the electric vehicle. The fuel cell is basically facilitate the capture of hydrogen and converting hydrogen power into useful energy, it is generally described as the reverse of that of the electrolysis. More precisely, it is an electrochemical and controlled combustion of hydrogen and oxygen, with simultaneous production of electricity, water and heat, according to a universally known global non-polluting chemical reaction : An elementary cell is made up of 3 elements:

- Two electrodes.
- An electrolyte.

The fuel cell supplies rather than stores electrical energy and continues to do so as long as the fuel supply is continuous.

The advantages of fuel cell are:

- \* It converts fuel into electricity efficiently.
- \* It produces zero or very low emissions. It produces zero or very low emissions.
- \* It operates quietly and can recover waste heat.
- \* In addition to its fuel flexibility, reliability and durability.

As for their disadvantages [4]:

- ★ The response time of fuel cells is relatively longer than that of batteries.
- ★ In addition, they are more expensive

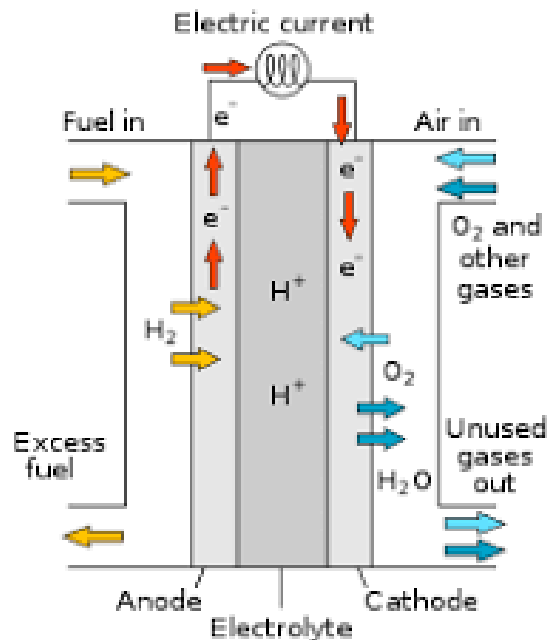


Figure 1.9: Fuel Cell Operating Principle

Direct electrical storage systems can also be divided into two large families, which are:

1. Accumulators
2. Super-capacitors

### 1.4.2.3 Accumulators

They store energy by transforming chemical energy. The accumulators consist of two electrochemical couples composed of two electrodes, immersed in an electrolyte. As soon as oxidation or reduction reactions occur which exchange electrons, the ions generated circulate in the electrolyte. To have a large stored energy, it is necessary, on the one hand, a large number of exchanged electrons, a reaction associating, a very oxidizing element and a very reducing element and on the other hand, it is necessary a perfect reversibility of the electrochemical processes, as well as low mass or low molar volume materials [5].

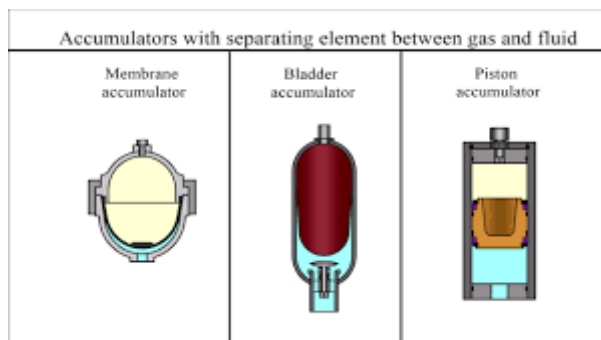


Figure 1.10: Accumulators

#### 1.4.2.4 Super capacitors

They store electrical energy in electrostatic form. The general operating principle of super capacitors is based on the formation of a double electrochemical layer at the interface of an electrolyte and a polarizable electrode with a large specific surface. The application of a potential difference across the terminals of the device leads to the ionic storage of charges at the two electrode-electrolyte interfaces which behave like two capacitors in series.

Super-capacitors are characterized by a specific energy 10 to 20 times lower than that of accumulators, but their specific power can be up to 10 times higher than that of lead batteries for example.

The batteries most used in electric vehicles are those made up of accumulators, for example lead-acid batteries, which have never left the scene for more than a century, and Nickel/Cadmium accumulators and lithium-ion batteries or li-ion which are more recent, with a much higher energy density than that of lead/acid batteries, and Nickel/Metal Hydride accumulators which can store twice as much energy as lead batteries and 35% of more than Nickel/Cadmium for equal weight.

Many studies propose the use of super capacitors in electric vehicles. The use of super-capacitors essentially makes it possible to operate the battery at a nominal operating rate and therefore to increase its lifespan.[5].



Figure 1.11: Super capacitors

The use of super capacitors in the automotive sector particularly meets the following needs:

- ▷ Starting and stresses at low temperature.
- ▷ Acceleration assistance and energy recovery.
- ▷ Supply of auxiliary organs

## 1.5 Electronic control

Electric traction for electric vehicles is achieved by an element controlling the energy transferred from the battery to the motor, which can be called electronic control . It allows optimization of the battery and motor and continuous self-diagnosis. It manages all the driver's commands according to the capabilities of the electric car. This is the reason why it receives a quantity of information such as the temperature, the speed of rotation, and the electric currents. This allows it, on the one hand, to carry out a report on the state of the vehicle, and on the other hand, to adjust the various commands applied to the electric motor in order to better manage the energy consumption [3].

### 1.5.1 Electrical energy converter

Power electronics are used to convert electrical energy and manage the flow of energy in the vehicle. According to the use of direct current or alternating current machine, the energy converters will have to be different. The nature of the energy source is of the continuous type . As a result, vehicles can be found on board:

- Alternating current to direct current converters (AC-DC), they are called rectifiers.
- Direct current to direct current (DC-DC) converters, called choppers.
- Direct current to alternating current (DC-AC) converters are called inverters.

#### 1.5.1.1 Choppers (DC-DC)

A chopper is a current converter which makes it possible to obtain, from a direct current voltage source of substantially constant value, controlled, adjustable voltages and currents, different from the input values and adapted to the requirements necessary for the supply of various receivers (motors, batteries, etc.). In an electric vehicle, choppers have two essential uses:

1. They are essential in supplying propulsion motors when these are DC motors.
2. They are necessary to adapt the voltage of the main battery to that of the electronic auxiliaries used (sensors, regulators, etc.)

Indeed, it is not possible to envisage the sudden connection of a DC motor to a fixed voltage energy source (accumulator battery for example) for the following reasons:

- No adjustment of the motor torque or the speed of the motor would not be possible.
- The transient state on direct energization of the motor would be destructive both electrically (overcurrent) and mechanically (over torque).

The use of a chopper makes it possible to maintain the motor current at the desired value while ensuring progressive adjustment and without noticeable loss of the motor voltage. It also makes it possible to adjust the torque and the speed of the engine and therefore of the vehicle in traction but also in electric braking [2].

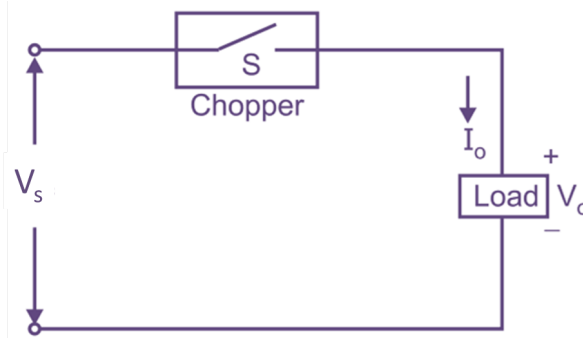


Figure 1.12: Chopper (DC-DC)

### 1.5.1.2 Inverter (DC-AC)

In electric traction, the inverter is a DC-AC converter, which makes it possible to obtain three phases of alternating current, of variable frequency from the battery current. In electric vehicles equipped with an alternating current motor, it is necessary to interpose between the energy source and the traction motor(s) a conversion device called an inverter, which transforms the electrical energy direct current into alternating current electrical energy and which makes it possible to carry out the control of the torque of the motors and the adjustment of the speed of the vehicle. DC-AC conversion can be done in multiple ways.

The main components in power converters are semiconductors. Current power semiconductors can be classified into three categories [2]:

1. Diode, closed or open state controlled by the power circuit.
2. Thyristor, closed by a control signal, but must be opened by the power circuit.
3. Transistor (switch controllable on opening and closing) opened and closed by a control signal.

### 1.5.1.3 Rectifier (AC/DC)

In an electric vehicle, rectifiers are used to transform energy alternating current electricity, supplied either by the general distribution network or by an alternator placed on board the vehicle, to a direct current which can be stored in an accumulator battery or in a large capacity battery .

## 1.6 Electric motor

Electric motor is a very simple component at the heart of the electric car, it plays on the forces of interactions (force vectors) between an electromagnet and a permanent magnet. It is used to convert the electrical energy that comes from the source, into mechanical energy used to propel the vehicle during

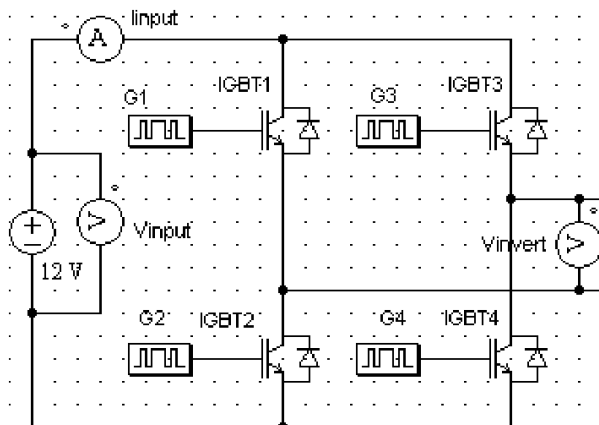


Figure 1.13: Inverter (DC-AC)

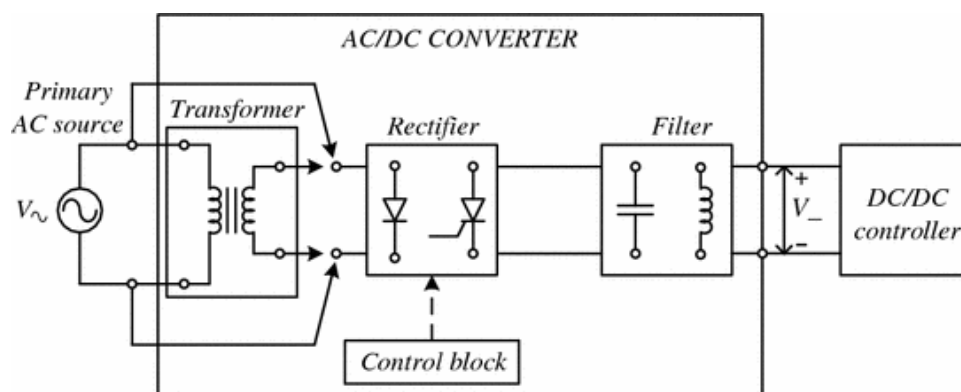


Figure 1.14: Rectifier (AC/DC)

traction phases, or reverse the energy mechanism into electrical energy during the braking phases, to allow recovery of energy (regeneration). During braking, the mechanical chain becomes partly the source of power, and the main power source (battery) becomes the receiver. Among the electric motors used in EVs, there are [4]:

### 1.6.1 DC motor

These motors have excellent characteristics for electric traction. Indeed, they are known for their ability to achieve high torque at low speeds and their torque-speed characteristics meet traction requirements. Motor speed is regulated through variable voltage, well suited in the role of vehicle thruster and easy to control. A DC motor is thus defined according to the way in which the motor is excited.

#### 1.6.1.1 Series-excited motor

It is the first that has been implemented in electric vehicles, because of its reliability of adaptation. The magnetic field is generated by electromagnets. The windings are connected in series with the armature, the same electric current passes through them.

### 1.6.1.2 Separately excited motor

Separately excited DC motors are suitable for flux weakening operation due to their decoupled torque and flux control characteristics; a flux weakening mode provides a wide range of constant power operation. Shunt motors are easier to control than series motors.

DC motors with separate excitation are controlled by a power chopper acting on the motor armature and a lower power chopper controlling the excitation or inductor. The electronics make it possible to optimize the set value of the armature and excitation current, according to the desired torque/speed characteristic, thanks to a system of relatively simple and inexpensive thyristors.

The control of DC motors has a complex structure, low efficiency and reliability and a constant need for maintenance. This is due to the presence of brushes and mechanical commutator. Brushed DC motors are difficult to downsize, making them heavier and more expensive. In addition, the brush/commutator friction limits the maximum speed of the motor.

## 1.6.2 AC motor

They are increasingly used in electric traction applications, being light and less expensive than DC motors. However, control electronics and controllers are more expensive and complex. The choice is therefore more oriented towards this solution, because significant developments in electronics are more likely than those concerning motor technology.

### 1.6.2.1 Asynchronous motor

For high-speed electric traction applications, the DC traction motor is increasingly being replaced by the asynchronous motor. The advantages are multiple:

- ✓ More robust mechanical construction (no commutator).
- ✓ For equivalent power, reduced dimensions and weight.
- ✓ For the same dimensions, higher power.
- ✓ Higher maximum rotation speed.
- ✓ No maintenance, since there is no collector.

Two types of asynchronous machine can be distinguished: 1) the slip-ring rotor asynchronous machine and 2) the squirrel-cage asynchronous machine. The latter is the most common.

The excess in power electronics equipment and adjustment and control circuits are the main drawbacks of this motor. However, this does not prevent the introduction of asynchronous motors in the field of electric traction, since the advantages mentioned predominate. The main advantages of the asynchronous motor are its reliability, its robustness and above all its cost. Although it is heavier and its efficiency is lower than that of synchronous machines. Their control requires the use of an electronic inverter. Its function is to convert the direct current from the batteries into three-phase alternating current, and to precisely control the operation of the engine during the acceleration phases and at cruising speed. In addition, the inverter transforms the alternating current generated by the motor during deceleration and braking into direct current to recharge the battery and improve motor braking. To ensure regulation, the inverter increases or decreases the frequency of the alternating current supplied to the motor according

to the driver's demand, and therefore the position of the accelerator pedal. The arrival of electronics has above all made it possible to considerably increase the speed of rotation [6].

### 1.6.2.2 Synchronous motor

The principle of operation of this motor is similar to that of DC motors, except that the commutation is this time electrical and not mechanical. Synchronous motors have good efficiency (about 90 %, inverter included), few thermal losses. They are lightweight and their manufacture is very flexible. Two types of synchronous machine can be distinguished.

**1.6.2.2.1 Permanent magnet synchronous motor (MSAP):** MSAPs are commonly used in different industrial applications in a power range from a certain number of Watts (servo motors) to several mega Watts (ship propulsion systems, etc.). The performance of MSAPs is intrinsically linked to the magnetic materials used within their structure.

**1.6.2.2.2 Wound-rotor synchronous motor (MSRB):** This engine can present a very interesting alternative. In comparison with the permanent magnet synchronous motor, the pole masses of the rotor are electromagnets supplied with direct current. The value of the induction can then vary by action on the excitation current. This type of motor has an additional degree of freedom, in comparison with that with permanent magnets; The excitation flux is created by a current which is injected into the rotor windings. In this machine, it is possible to choose the operating point of the machine. It easily gives the possibility of fluxing which can be carried out by a simple reduction of the excitation current. It is possible to adapt control laws to optimize performance.

**1.6.2.2.3 Variable reluctance synchronous motor (MRV):** This type of engine has a very high power/weight ratio and low cost. This engine produces a very pulsating torque at high speed causing mechanical vibration problems and generates an acoustic noise higher than all its competitors.

## 1.7 How Electric Vehicule Works

Electric cars contain a battery which stores energy and recharges in using the electrical network, and one or more electric motors with a system of control and a battery charger.

The battery is connected to the electric motor via a regulator and a transformer. The regulator is used to adjust the intensity of current supplied to the motor. Its operation is very simple: when the motorist presses the lever (accelerator), the battery releases current. The converter then converts the direct current (DC) from the battery into alternating current (AC) to drive the motor (in the case of the alternating current motor).

The converter is an integral part of the engine. The strong point of the electric vehicle is its electromechanical transmission chain. Indeed, the car needs high torque at low speeds to be able to accelerate and reduce torque at cruising speeds. These properties are those of the electric motor [5].

## 1.8 Different types of electric vehicles

There are two main families of electric vehicles: 1) All electric and 2) Hybrid vehicles which use an electric motor to improve the performance of the thermal part and increase the range between two fill-ups.

### 1.8.1 Hybrid vehicles

A Hybrid automobile is an automobile using two storage of distinct on-board energy to move, one of which is electrical in nature. Hybrid technologies were invented for several reasons: respect for the environment, driver comfort, better performance, but also to improve the efficiency of the thermal part and increase the range between two fill-ups. A hybrid vehicle is the combination of an electric motorization with a thermal motorization, ensuring the propulsion of the vehicle. Hybrid vehicles are an exciting innovation in technology. These vehicles typically include an internal combustion engine, electric motor, generator, and battery pack. It is possible to vary the nature, configuration and integration of these components in order to maximize the performance and efficiency of the vehicle and to reduce emissions.

The hybrid vehicle is equipped with a powertrain combining: A generator, which is reversible, characterized by a high specific energy ensuring the autonomy of the vehicle, and which is capable of supplying the average power necessary for the vehicle. A reversible energy accumulator, providing more power than the generator and having an energy at least equal to the kinetic energy of the vehicle at full load. A transmission and control system, capable of distributing the flows, these are the refluxes of energy between generator, accumulator and use [3].

#### 1.8.1.1 Architecture of Hybrid vehicles

The architecture of hybrid vehicles can be summed up in three essential variants:

**Series Engine Hybrids:** The series hybrid system allows the electric motor to direct the rotation of the wheels on its own using the power generated by the internal combustion engine. A series hybrid is made up of an electric motor, a heat engine, a generator, a battery and an inverter. At low speeds, the internal combustion engine is used intermittently to power either the electric motor or to recharge the battery. The all-electric is used in town, on the road the heat engine ensures the recharging of the battery as well as the supply of the electric motor. The series name comes from the fact that the heat engine is directly linked in series to the electric motor [3].

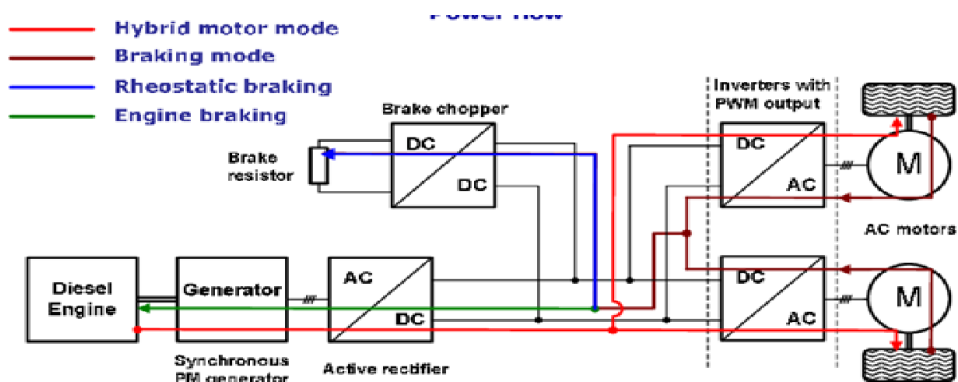


Figure 1.15: Architecture of Series Engine Hybrids Car

**Hybrids with motors in parallel:** The electric and thermal motors both ensure the rotation of the wheels, on the other hand, it is the electric motor which recharges the battery. A parallel hybrid consists of a heat engine, an electric motor, a battery, an inverter, and a transmission. The electric motor is powered this time by the battery and not by the heat engine, it also works as a generator to recharge the battery. The disadvantage is that it cannot generate electricity while driving. Once again, the electric

motor operates during city driving and the heat engine during the highest power demands on the road. The name parallel comes from the fact that the current is parallel [1].

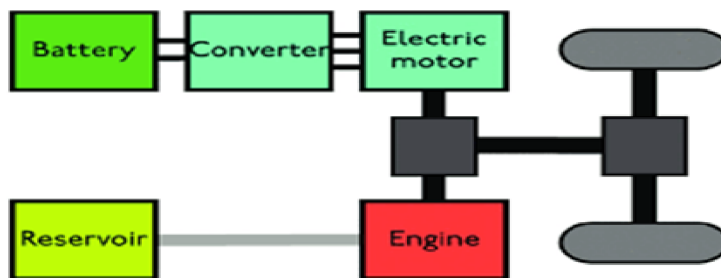


Figure 1.16: Architecture of Hybrids with motors in parallel

**Dual hybrid (series-parallel):** The series/parallel system is the combination of the electric and thermal motor allowing the rotation of the wheels by providing electricity to recharge the battery via the generator. This system has the advantage of being able to select the motors either electric or thermal as well as a permanent recharging of the batteries. It is made up of an electric motor, a heat engine, a generator, an energy distributor, a power supply control module (inverter/converter). The splitter makes it possible to operate the electric motor as well as to produce electricity to recharge the batteries, this while trying to obtain the best possible performance depending on the driving city, road, etc.

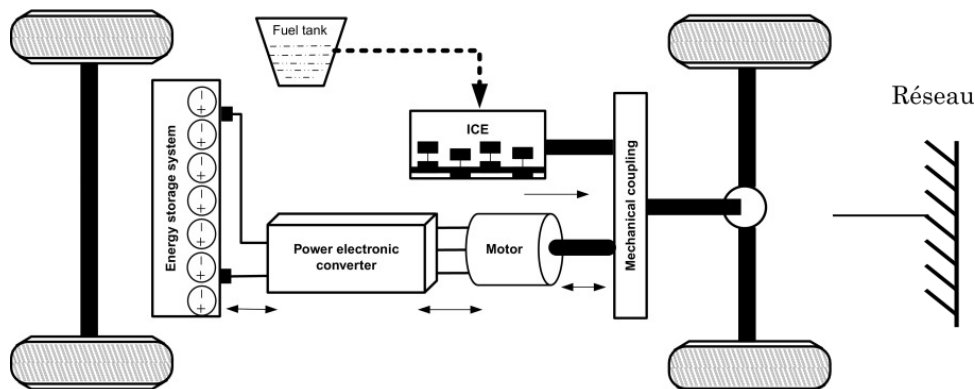


Figure 1.17: Architecture of dual hybrids series-parallel

## 1.9 100% Electric vehicles

An Electric Vehicle is a vehicle propelled by a motor running exclusively on electric power. In other words, the driving force is transmitted to the wheels by one or more electric motors depending on the transmission solution adopted. It is a complex system made up of very varied components of different natures (mechanical, electrical, electrochemical) in interaction. Its behavior is therefore sensitive to any variation in the characteristics of one of its components through these interactions [7].

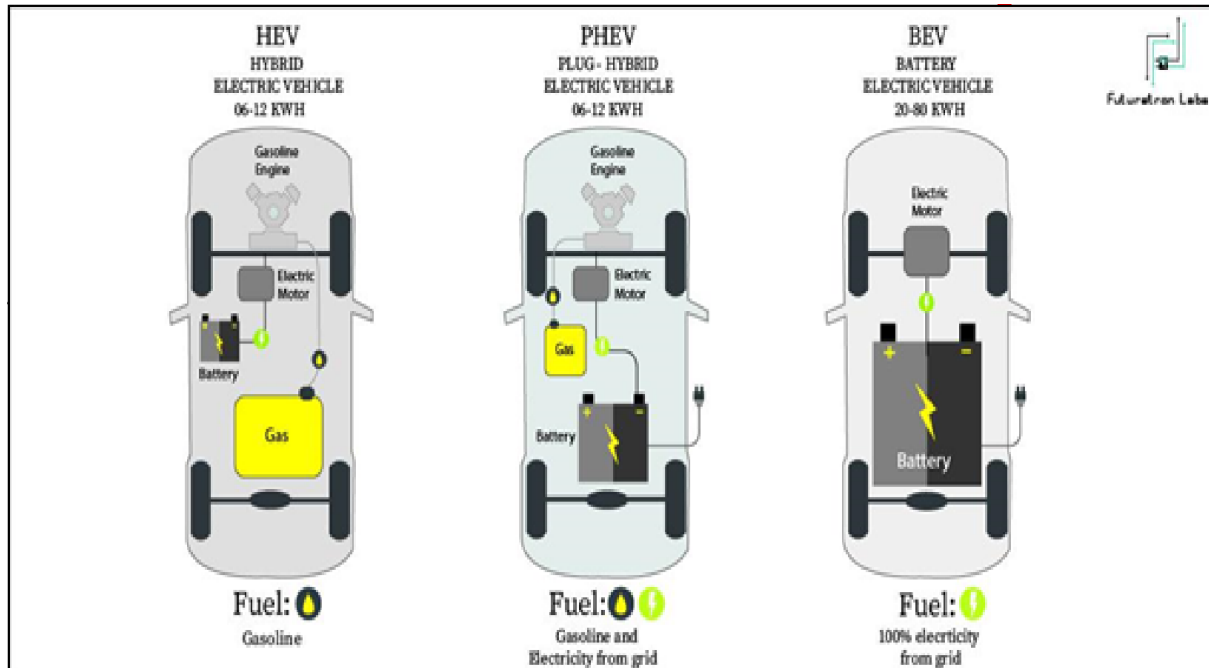


Figure 1.18: Architecture of different type of electric vehicles

## 1.10 General description of the traction chain

The traction chain of an all-electric vehicle can be broken down into the elements. It is, if we start from the AC power supply network, the battery charger, the electrochemical battery of the on-board source of electrical energy, the static converter assembly of the electric motor and the control and, finally, of the mechanical transmission whose function is to adapt the mechanical characteristic of the load to that of the motor. For the analysis of the total consumption, it is also necessary to take into account the auxiliaries such as the cooling system (air or water) of the engine and its electronic converter.

The traction chain of an electric vehicle is simpler than that of a thermal vehicle. It also has interesting properties such as silent operation almost total as well as the ability to recharge during the vehicle's deceleration phases, in addition there are zero polluting emissions at the place of use [2].

## 1.11 Different traction architectures

### 1.11.1 Single motor electric vehicles (direct current machine)

It is an architecture with a DC motor, a battery, a drive (a chopper reversible), a direct current machine, a differential reducer (speed reduction, increase in torque).

### 1.11.2 Multi-motor electric vehicles (alternating current machine)

In this type, the energy chain is doubled, it is an architecture with synchronous motor (in the wheel), a battery, two drives (inverter), two synchronous machines. The inverter is used to convert the DC electric current supplied by the battery into alternating current necessary for the motor of the electric car.

## 1.12 Architecture of an EV

The simplest solution for making an electric vehicle is to build it on the basis of an existing thermal vehicle, replacing the thermal engine with an electric motor. However, the mechanical transmission can be simplified. The ability of electric motors to start at high torque and operate over a wide speed range makes it possible to eliminate the clutch, or even the gearbox. By on the other hand, as the torque is a dimensioned quantity, the absence of a gearbox implies a heavier, more bulky and therefore more expensive engine. Also, to reduce the onboard mass, EVs can be designed with a reduction gear that allows the electric motor to work at high speed [4]. This reducer makes it possible to reduce the size of the motor. This traction chain centered around a single traction motor coupled to a fixed-ratio gearbox represents the so-called classic solution for EV architecture. The classic traction chain of an EV includes the energy source, the converter, the electric motor, the mechanical transmission including the differential and the wheels. The traction system is a set of organs through which the flow of energy passes, and which provide a vehicle with its ability to move. It is made up of a traction chain and an on-board energy generator.

- Traction chain: Part of the traction system ensuring the mechanical transmission of movement. It is made up of the wheels, the transmission differential or gearbox (BV) and a motor converting the energy coming out of the on-board generator into mechanical energy.

- Generator or onboard energy source: Component of the traction system ensuring the energy storage and adaptation. It is made up of a storage system and an adaptation system (converter and/or transformer).

- Energy converter: System that changes the nature of energy.

- Energy transformer: System that retains the nature of the energy but changes its type (gearbox, DC/AC electric converter).

- Energy typing: Characterizes the parameters of an energy of the same nature (for electricity: voltage, current, frequency,).

- Nature of energy: Characterizes the different forms that energy can take (mechanical, electrical, etc.). A differential is a mechanical system whose function is to distribute a rotational speed by distribution of the kinematic force, in an adaptive way , immediate and automatic, to the needs of a mechanical assembly.

- A gear is a mechanical system made up of two toothed wheels used to transmit rotational movement.

- A reducer is a gear system whose transmission ratio is less than 1, to increase the motor torque by one revolution [4].

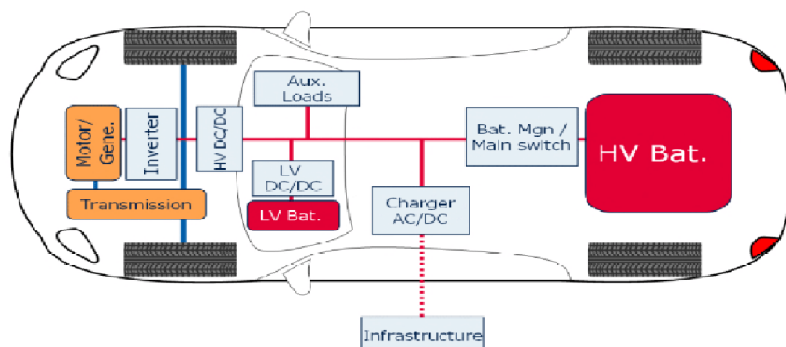


Figure 1.19: Architecture of an EV

## 1.13 Advantages and disadvantages of electric vehicles

### 1.13.1 Advantages of electric vehicles

The advantages of the electric vehicles can be summarized in the following points [7]:

- Electric vehicles are devoid of noise pollution since they are completely silent.
- Electric vehicles are fun to drive, with a smooth ride quality, due to continuous and gradual accelerations because the engine never stalls (no clutch).
- The technical architecture of electric vehicles is simple, it is composed of 6000 parts less than a traditional car.
- These vehicles are easier to maintain and their expenses are reduced by 30 to 40 % (for example the electric motor does not require draining). Moreover, the occasions of breakdowns are 3 times less numerous.
- Electric vehicles do not consume energy in traffic jams and braking (the car recharges itself). They are therefore very suitable for the urban environment. which will be the main type of habitat in the future (megalopolis).
- The electric motor has an energy efficiency 3 times higher than that of a thermal motor.
- The start is very fast, it is enough to press a button for it to start or running (nor the problems of starting during cold winter weather).
- The main advantage is independence from oil.

### 1.13.2 Disadvantages of hybrid vehicles

The major points of the disadvantages are [7]:

- \* The price remains very high compared to 'classic' cars.
- \* The weight is heavier due to the use of additional parts.
- \* The duration of recharging electric batteries is still long. Furthermore, when in use, the electric motor does not produce heat. The cabin of the car is not hot. For better comfort (air conditioning, radio, etc.), the battery discharge is accelerated.
- \* Battery life and electric motor power are not still very important.

## 1.14 New Achievements

In recent years, the development of the electric vehicle has made significant progress, the global awareness of the environmental issue and the desire of car manufacturers to carry out the energy and technological transition. As early as 2010, several manufacturers launched the marketing of their electric vehicle models. Most of these vehicles are relatively small in size, to reduce consumption. They are a good alternative to gasoline and diesel vehicles for urban use, the Bluecar mise is a good example. It is equipped with a battery Lithium Metal Polymer, which offers, according to its designers, a range of 250km and a full recharge in 8 hours. As far as battery charging is concerned, Renault offers three

processes for the Fluence.ZE: slow charging on the mains (approximately 8 hours), fast partial charging on terminals (80% in approximately 20 minutes), and finally a charging system. rapid exchange of batteries, "Quickdrop" allowing the battery to be replaced in 3 minutes. For this type of vehicle, the advertised autonomy is 60km [8].

## **1.15 Conclusion**

During this chapter, we have presented a state of the art on electric vehicles, a brief history and the elements that make up this kind of vehicle were presented in detail, then we have presented the different types of electric vehicles and we concluded by giving the advantages and disadvantages of these vehicles.

## 2.1 Introduction

The induction machine, or asynchronous machine, is an alternating current electrical machine with no connection between the stator and the rotor. The term asynchronous comes from the fact that the speed of these machines is not necessarily proportional to the frequency of the currents which cross them. It is used in a range of power applications from a few Watts to several MW. These squirrel cage machines are prominent in all industrial sectors. They are the most preferred choice for performance oriented electric vehicles due to their robustness, their simplicity of construction and their low cost [6].

In this chapter, the principle of operation of the induction motor will be well explained as well as the manufacture of its two main parts (Stator, Rotor) and the role of each of them inside the motor will be clarified, then its mathematical model will be given in detail.

## 2.2 Definition of the asynchronous machine

An asynchronous motor is an alternating current motor for which the rotational speed of the shaft is different from the rotational speed of the rotating magnetic field. An induction motor is an asynchronous motor whose magnetic circuit is associated with two or more electrical circuits moving relative to each other and in which energy is transferred from the fixed part to the moving part, or conversely, by electromagnetic induction (Figure 2.1).

## 2.3 Constitution

The asynchronous motor is formed of [9]:

### 2.3.1 Stator

It is the fixed part of the engine. A casing in cast iron or light alloy encloses a ring of thin sheets (about 0.5mm thick) in silicon steel. The sheets are isolated from each other by oxidation or by an insulating varnish. The 'lamination' of the magnetic circuit reduces the losses by hysteresis and eddy currents. The laminations are provided with notches in which the stator windings are placed, intended to produce the rotating field (three windings in the case of a three-phase motor). Each winding consists of several coils.

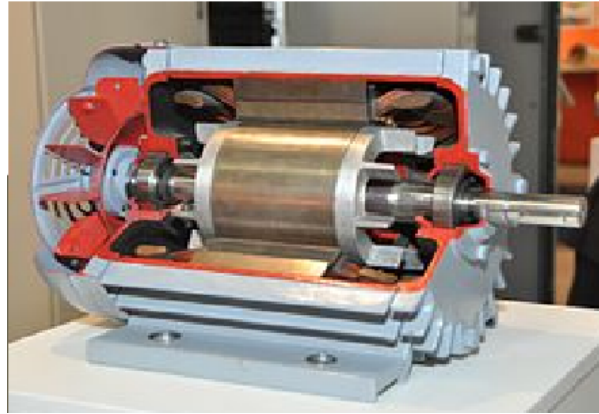


Figure 2.1: The asynchronous machine.

The mode of coupling of these coils between them defines the number of pairs of poles of the motor, therefore the speed of rotation.

The stator consists of a wound winding distributed in the slots of the magnetic circuit. This magnetic circuit consists of a stack of sheets in which notches are cut parallel to the axis of the machine. The slot conductors make it possible to create in the air gap the magnetic field at the origin of the electromagnetic conversion.

The stator winding can be broken down into two parts: the slot conductors and the magnetic ones at the origin of the electromagnetic conversion. The coil heads allow currents to close by organizing the judicious flow of currents from one slot conductor to another. The objective is to obtain on the surface of the air gap the most sinusoidal current distribution possible, in order to limit the ripples of the electromagnetic torque [9].

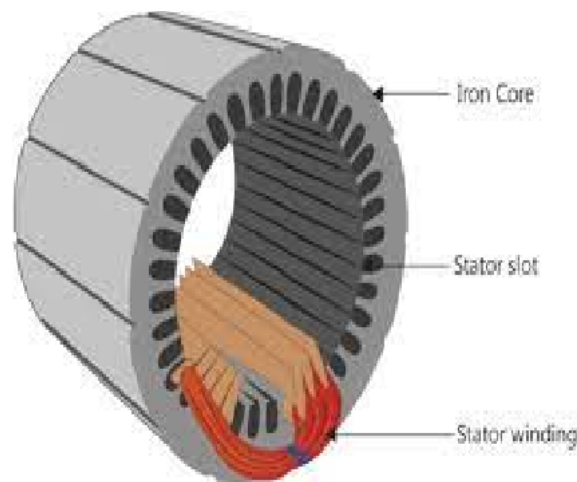


Figure 2.2: The stator of the asynchronous machine.

### 2.3.2 Rotor

It is the moving part of the engine. It consists of a stack of thin sheets isolated from each other and forming a keyed cylinder on the motor shaft. This element, due to its technology, makes it possible to distinguish between two families of asynchronous motors: those whose rotor is said to be 'cage', and those whose wound rotor is said to be 'with rings', which makes it possible to put in rotation the mechanical

load, just like the stator, the magnetic circuit is made up of steel sheets which are in general, of the same origin as that used for the construction of the stator [10].

### 2.3.2.1 Wound rotor

It is made in the same way as the stator winding (insertion of the windings in the rotor slots). The rotor phases are then available thanks to a system of brush rings positioned on the machine shaft. The rotor windings locate in the notches located at the peripheral of the rotor. These windings are wound from the machine to obtain a three-phase winding at even  $P$  of pole. The rotor windings are always star-coupled, and the three accessible terminals are connected to the stator frame using a system consisting of three rings and three fixed brushes.

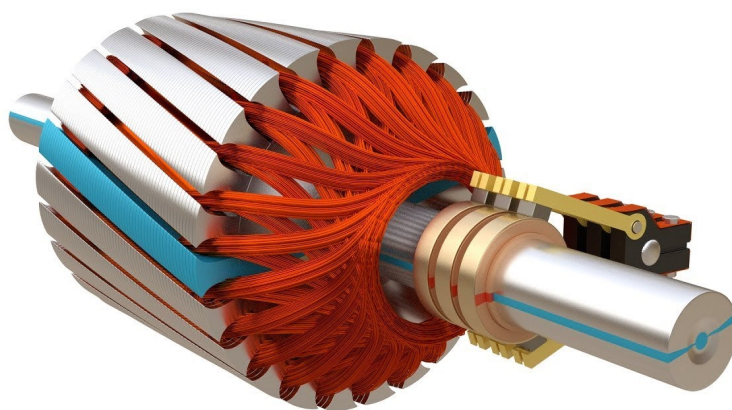


Figure 2.3: Wound rotor of the asynchronous machine.

### 2.3.2.2 Cage rotor

In the cage rotor, the short-circuit rings allow currents to flow from one slot conductor (rotor bar) to the other. These conductive bars are regularly distributed, and constitute the circuit of the rotor. This cage is inserted inside a magnetic circuit made up of sheet metal discs stacked on the shaft of the machine similar to that of the wound rotor motor. In the case of the squirrel cage rotor, the conductors are made by casting an aluminum alloy, or by massive copper bars drilled and fretted in the rotor laminations or very little insulation between the rotor bars and the magnetic laminations, but their resistance is low enough for the leakage currents in the laminations to be negligible, except when there is a bar break. The squirrel cage motor is much simpler to build than the coil rotor, and therefore its cost price remains lower. In addition, it has a greater robustness than that of the coil, it constitutes the largest part of the fleet of asynchronous motors currently in service.

## 2.3.3 Bearings

Support members, these constitute the mechanical part thus allowing the rotation of the motor shaft.

## 2.3.4 Air gap

This part is non-magnetic (it is the vacuum between the rotor and the stator).

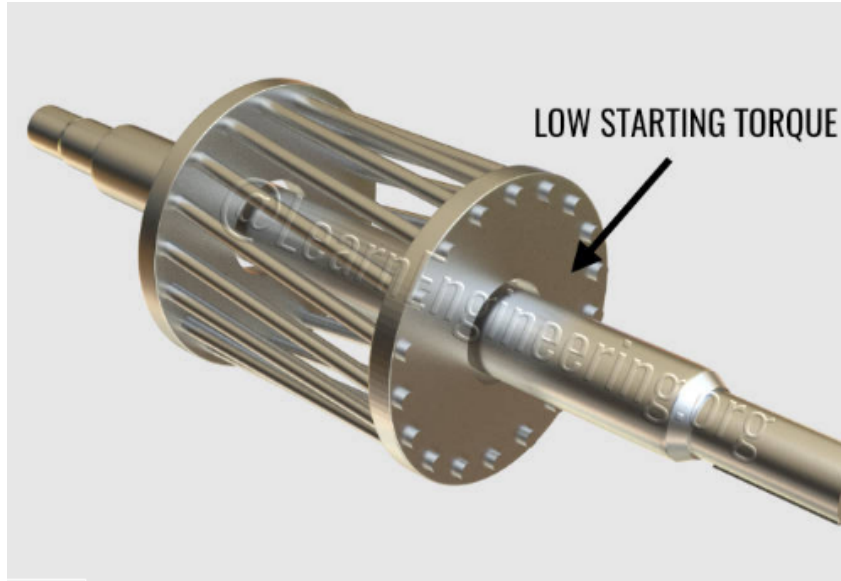


Figure 2.4: The cage rotor of the asynchronous machine

## 2.4 Principle of operation of an asynchronous machine

As mentioned previously, the asynchronous machine consists mainly of a stator and a rotor. These elements are made using special materials and in such a way that the induction motor can work in the best possible way. The stator, the fixed part of the machine, is made up of  $3p$  (where  $p$  designates the number of pairs of poles) coils powered by a system of three-phase voltage and current of frequency  $f$  supplied either by the electrical network or by the drive.

The phase shift between the voltages and currents of the three phases is  $\frac{2\pi}{3}$  radians. However, each  $p$  series features three coils that are separated from  $\frac{2\pi}{3}$  each other. In an asynchronous electrical machine, the stator windings are distributed in space and offset from each other by  $120^\circ$ . The same remarks apply to the rotor whether it is wound or caged.

So we can bring back the explanation of the principle of operation of the asynchronous machine with 3 windings which we note  $a$ ,  $b$  and  $c$ , illustrates a symbolic diagram of the stator. The operating principle of the asynchronous machine is based entirely on the law of induction; the asynchronous machine is considered as a rotating magnetic field transformer whose stator is comparable to the primary winding and the rotor has the secondary winding in short circuit. This operation is based on the principle of the electromagnetic interaction of the rotating field, created by the three-phase currents supplied to the stator winding by the network, and currents induced in the rotor winding when its conductors are broken by the rotating field. When the rotor turns at a speed different from synchronism, the application of Faraday's law to one of the rotor windings shows that it becomes the seat of an electromotive force which, being short-circuited on the windings, will give rise to a current whose intensity is limited by the impedance of the latter. The interaction between this current and the sliding field will give rise to forces acting on the strands of the rotor whose moment with respect to the axis of rotation will constitute the torque of the machine when the field is sinusoidal, so the rotation speed is [11]:

$$n_1 = \frac{f}{p} [tr/s] \quad (2.1)$$

With:

$f$ : the power supply frequency.

$p$ : represents the number of pairs of poles.

The electromagnetic interaction of the two parts of the machine is possible only when the speed of the rotating field ( $n_1$ ) differs from that of the rotor ( $n$ ), that is, when  $n \neq n_1$ , because otherwise ( $n = n_1$ ), the field would be stationary with respect to the rotor and no current would be induced in the rotor winding.

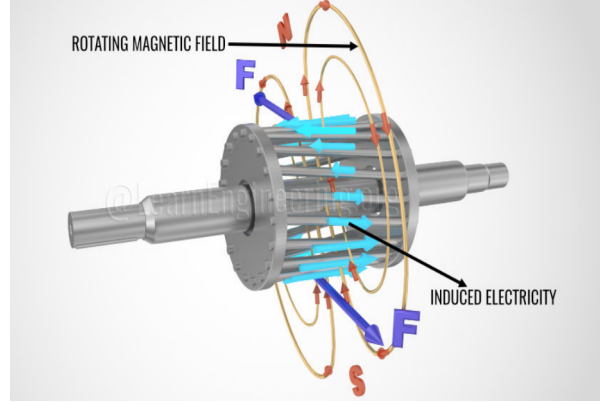


Figure 2.5: Magnetic field generation

The  $g = \frac{n_1 - n}{n_1}$  is called slip of the asynchronous machine.

The angle  $\theta$  between the two vectors the magnetic moment  $\vec{M}$  of the rotor (directed from the south pole towards the north pole) and the rotating field  $\vec{B}_t$  is called angular shift. The moment of the couple  $\vec{T}$  acting on the rotor depends on the angle  $\theta$  :

$$\vec{T} = \vec{M} \wedge \vec{B}_t \quad (2.2)$$

$$T = M \cdot B_t \cdot \sin \theta \quad (2.3)$$

If  $\theta$  is positive ( $\theta$  is counted positively in the direction of rotation) then the rotor follows the field rotating, the moment of the torque is positive (orientation of the torques from the direction of rotation by the corkscrew rule) and the machine works as a motor. With no load, when the motor does not provide any useful torque, the angle  $\theta$  is small, but the torque useful of the motor increases, the more the angle  $\theta$  increases. The maximum torque is obtained when  $\theta = \frac{\pi}{2}$  (for 2 pairs of poles). If we try to make the motor provide more torque,  $\theta$  increases and becomes greater than  $\frac{\pi}{2}$ , the motor torque decreases instead of increasing and the rotor stalls, it does not happen more to follow the rotating field. The rotor eventually stops and safety devices must cut off the stator power supply to avoid large overcurrents. If  $\theta$  is negative, the rotor precedes the rotating field, the torque moment is negative and has tendency to brake the rotor, the machine operates as an alternator, i.e. it absorbs mechanical power and provides electrical power.

The air gap is the empty space between the stator and the rotor, his rotating field has a so-called synchronism rotation speed equal to:

$$n_s = \frac{f}{p} [tr/s] \quad (2.4)$$

$$\Omega_s = \omega_s = \frac{2\psi f}{p} [rad/s] \quad (2.5)$$

with:

$n$ : the number of revolutions per second of rotating field;

$f$ : the frequency of the asynchronous machine;

$p$  : represents the number of pairs of poles;

$W_s$  or  $\Omega_s$  : the speed of the rotating field in radians per second.

The magnetic field created by the stator rotates around the rotor (at a standstill during start-up) in order to create, thanks to its flux, induced currents in the rotor bars. According to Lenz's law, induced currents are opposed by their effects to the cause which gave rise to them. The flow of currents in the rotor cage is possible, because the circuit is closed, and therefore, Laplace forces result. This force is different at every point of the cage. This phenomenon makes it possible to create a torque and start the asynchronous motor. Indeed, if the flux of the magnetic field of the stator did not vary around the rotor, the rotor currents would be equal, as well as the Laplace forces would compensate each other. If there is no difference in force, the sum of the forces would be zero as well as the torque. The engine could not start. The number of poles at the rotor must be equal to the number of poles at the stator. For a squirrel cage, this condition is automatically true [12].

## 2.5 Modeling of the asynchronous machine

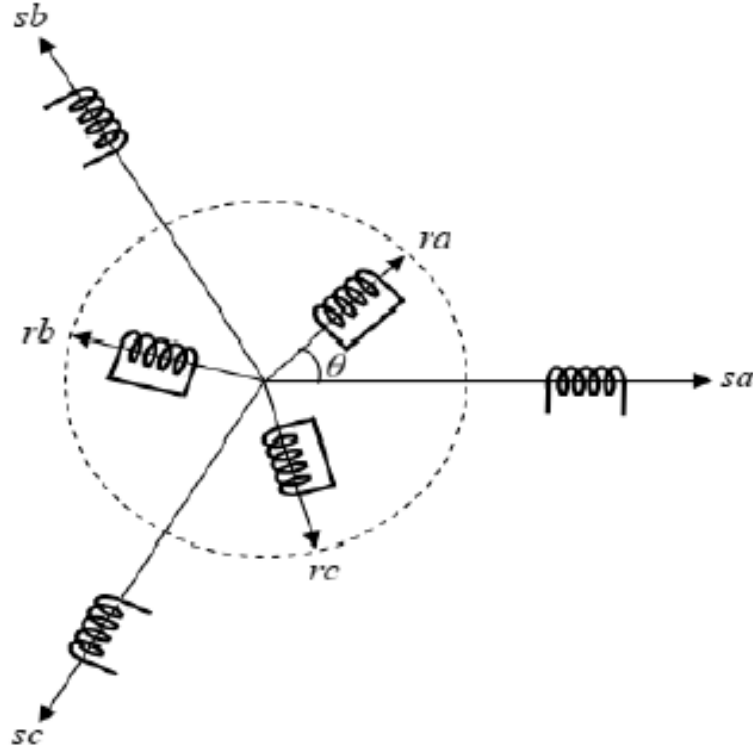
It is common to use PARK theory to model alternating current machines. By describing the rotating machine in the appropriate frame of reference, the equations of state are simplified. This makes their study and exploitation easier. These simplifications come from the internal properties of the alternating current machine, The modeling of the asynchronous machine is based on a certain number simplifying assumptions, which are:

### Simplifying assumptions

- Perfect symmetry of construction.
- The magnetic circuit is not saturated.
- The variation of winding resistances with temperature is negligible.
- The air gap is constant.
- The values of the self and mutual inductances are independent of the intensities currents.
- The iron losses and the losses by hysteresis and by eddy currents are nil.
- The distribution in the air gap of the magnetomotive force and that of the flux are sinusoidal.

### 2.5.1 Dynamic model of the asynchronous machine

In the three-phase reference, the three vectors  $A, B, C$  are oriented along the axes of the three stator windings of the machine. The rotor can be modeled by three identical short-circuited windings whose voltage across the terminals of each winding is zero. the  $A$  axis is taken as a reference, and the angle  $\theta$  defines the position of the rotor relative to the stator.

Figure 2.6: Model of the asynchronous machine in  $abc$  axis

## 2.5.2 General equations of the three-phase asynchronous machine

Under these conditions, if we consider that the induction motor is three-phase with the stator and the rotor. The three types of equations expressing the behavior of the engine are:

### 2.5.2.1 Electrical equations

Taking into account the assumptions mentioned above, the electrical equations of the stator and rotor voltages can be written as follows:

At the stator:

$$V_s(abc) = R_s \cdot I_s(abc) + d\psi_s(abc)/dt \quad (2.6)$$

$$\begin{bmatrix} V_{sa} \\ V_{sb} \\ V_{sc} \end{bmatrix} = R_s \cdot \begin{pmatrix} I_{sa} \\ I_{sb} \\ I_{sc} \end{pmatrix} + d/dt \cdot \begin{bmatrix} \psi_{sa} \\ \psi_{sb} \\ \psi_{sc} \end{bmatrix} \quad (2.7)$$

At the rotor:

$$V_r(abc) = R_r \cdot I_r(abc) + d\psi_r(abc)/dt \quad (2.8)$$

$$\begin{bmatrix} V_{ra} \\ V_{rb} \\ V_{rc} \end{bmatrix} = R_r \cdot \begin{pmatrix} I_{ra} \\ I_{rb} \\ I_{rc} \end{pmatrix} + d/dt \cdot \begin{bmatrix} \psi_{ra} \\ \psi_{rb} \\ \psi_{rc} \end{bmatrix} \quad (2.9)$$

With :

$V_{sa}, V_{sb}, V_{sc}$ : the three stator voltages;

$I_{sa}, I_{sb}, I_{sc}$ : the three stator currents;

$I_{ra}, I_{rb}, I_{rc}$  : the three rotor currents;

$\psi_{sa}, \psi_{sb}, \psi_{sc}$  : fluxes through the three phases of the stator;

$\psi_{ra}, \psi_{rb}, \psi_{rc}$ : fluxes through the three phases of the rotor;

### 2.5.2.2 Magnetic equation

The flows of the machine are expressed by:

At the stator:

$$\psi_s(abc) = L_s \cdot I_s(abc) + M_{sr} \cdot I_r(abc) \quad (2.10)$$

$$\begin{bmatrix} \psi_{sa} \\ \psi_{sb} \\ \psi_{sc} \end{bmatrix} = L_s \cdot \begin{bmatrix} I_{sa} \\ I_{sb} \\ I_{sc} \end{bmatrix} + M_{sr} \cdot \begin{bmatrix} \psi_{ra} \\ \psi_{rb} \\ \psi_{rc} \end{bmatrix} \quad (2.11)$$

At the rotor:

$$\psi_r(abc) = L_r \cdot I_r(abc) + M_{rs} \cdot I_s(abc) \quad (2.12)$$

$$\begin{bmatrix} \psi_{ra} \\ \psi_{rb} \\ V_{rc} \end{bmatrix} = L_r \cdot \begin{bmatrix} I_{ra} \\ I_{rb} \\ I_{rc} \end{bmatrix} + M_{rs} \cdot \begin{bmatrix} \psi_{sa} \\ \psi_{sb} \\ \psi_{sc} \end{bmatrix} \quad (2.13)$$

Such as:

$M_{sr} = M_{rs}^T$  With :

$M_{sr}, M_{rs}$ : the matrix of mutual stator/rotor inductances.;

$L_s, L_r$ : the stator/rotor inductance matrix;

The inductance matrices are defined by:

$$\begin{bmatrix} L_s \end{bmatrix} \begin{bmatrix} L_{ms} + L_{ls} & -\frac{L_{ms}}{2} & -\frac{L_{ms}}{2} \\ -\frac{L_{ms}}{2} & L_{ms} + L_{ls} & -\frac{L_{ms}}{2} \\ -\frac{L_{ms}}{2} & -\frac{L_{ms}}{2} & L_{ms} + L_{ls} \end{bmatrix} \quad (2.14)$$

$$\begin{bmatrix} L_r \end{bmatrix} \begin{bmatrix} L_{mr} + L_{lr} & -\frac{L_{mr}}{2} & -\frac{L_{mr}}{2} \\ -\frac{L_{mr}}{2} & L_{mr} + L_{lr} & -\frac{L_{mr}}{2} \\ -\frac{L_{mr}}{2} & -\frac{L_{mr}}{2} & L_{mr} + L_{lr} \end{bmatrix} \quad (2.15)$$

$$\begin{bmatrix} L_r \end{bmatrix} = L_{sr} \cdot \begin{bmatrix} \cos(\theta) & \cos(\theta + \frac{2\pi}{3}) & \cos(\theta - \frac{2\pi}{3}) \\ \cos(\theta - \frac{2\pi}{3}) & \cos(\theta) & \cos(\theta + \frac{2\pi}{3}) \\ \cos(\theta + \frac{2\pi}{3}) & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta) \end{bmatrix} \quad (2.16)$$

With :

$L_{ms}$ : stator magnetization inductance;

$L_{mr}$ : rotor magnetization inductance;

$L_{ls}$ : stator leakage inductance;

$L_{lr}$ : rotor leakage inductance.;

$L_s$ : stator inductance matrix.;  
 $L_r$ : rotor inductance matrix;  
 $L_{sr}$ : stator-rotor mutual inductance matrix.

### 2.5.2.3 Mechanical equation

The study of the characteristics of the asynchronous machine introduces variation not only of the electrical parameters (voltage, current, flux), but also of the mechanical parameters (torque, speed). The torque formula is given by the following equation:

$$[C_{em}] = p \cdot [i_s(abc)^T] \cdot \frac{d}{dt} [M_{sr}] [i_r(abc)] \quad (2.17)$$

After determining the electrical, magnetic and mechanical equations, we end up with a system of six differential equations and an equation expressing the torque, hence the complexity of solving our system analytically, we will be required to transfer from a three-phase system to a two-phase system [13].

### 2.5.3 Three-phase to two-phase transformation

It consists of transferring from a three-phase system to a two-phase system, which is in fact only a basic change in the physical quantities (voltages, fluxes, and currents), it leads to relations independent of the angle  $\theta$  and the order reduction of the machine equations [13].

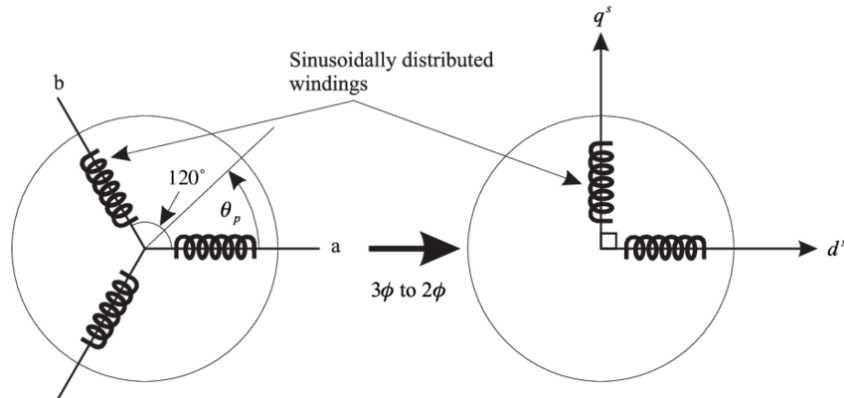


Figure 2.7: Three-phase to two-phase transformation

Figure 2.7 identified the different frames of reference. The most famous transformation is that of Park.

#### 2.5.3.1 Park transformation

For each set of quantities (stator and rotor), we apply the transformation of Park in order to simplify the equations, and therefore the model. The landmarks of the Park transformation of the stator quantities and those of the rotor quantities must coincide.

Indeed, if we note by  $\theta_s$  (resp by  $\theta_r$ ) the angle of the transformation of Park of the stator quantities (resp. Rotorique). This is done by linking the angles  $\theta_s$  and  $\theta_r$  by the following relationship:

$$\theta_s = \theta_r + \theta \quad (2.18)$$

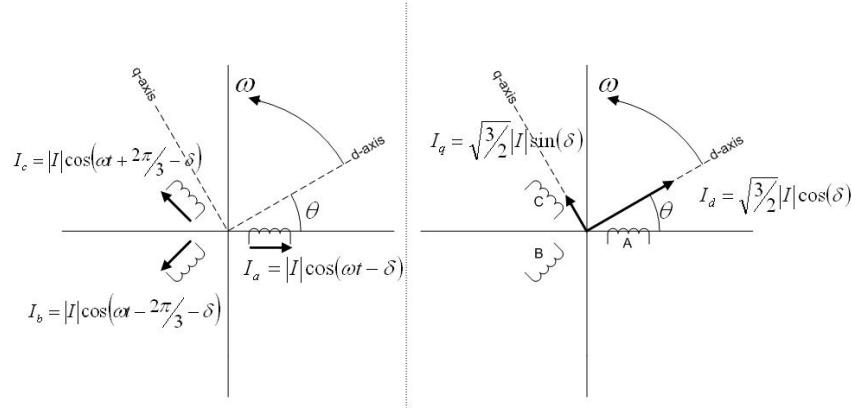


Figure 2.8: Park transformation

$$X_{dq} = [P(\theta)] \cdot X_{(abc)} \quad (2.19)$$

Such as :

$X$ : maybe voltage, current or flux.

$P(\theta)$ : matrix of the Park transformation defined by:

$$p[(\theta)] = \sqrt{\frac{3}{2}} \begin{pmatrix} \cos(\theta) & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \\ -\sin(\theta) & -\sin(\theta - \frac{2\pi}{3}) & -\sin(\theta + \frac{2\pi}{3}) \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{pmatrix} \quad (2.20)$$

and  $[P(\theta)]^{-1}$  is the inverse Park matrix gives by:

$$[P(\theta)]^{-1} = \sqrt{\frac{2}{3}} \begin{pmatrix} \cos(\theta) & -\sin(\theta) & \frac{1}{\sqrt{2}} \\ \cos(\theta - \frac{2\pi}{3}) & -\sin(\theta - \frac{2\pi}{3}) & \frac{1}{\sqrt{2}} \\ \cos(\theta + \frac{2\pi}{3}) & -\sin(\theta + \frac{2\pi}{3}) & \frac{1}{\sqrt{2}} \end{pmatrix} \quad (2.21)$$

With :

$\theta$ : the angle corresponds to the position of the frame chosen for the transformation.

$\theta_s/r$ : the angle of the stator/rotor.

## 2.5.4 Park transformation applied to MAS

The system of equations in the reference  $abc$  has time-varying coefficients. This which makes its resolution complex and difficult. To solve this problem, we use the Park transformation to have a system of differential equations with constants coefficients .

After applying the Park transformation, we find the following equations [14]:

### 2.5.4.1 Voltage equations

By applying the Park transformation to the voltages in the frame  $abc$ , as shown in the following equation:

$$V_{dq} = [P(\theta)] \cdot V_{(abc)} \quad (2.22)$$

We obtain the following equations:

$$\begin{cases} V_{sd} = R_s \cdot I_{sd} + \frac{d\psi_{sd}}{dt} - \omega_s \cdot \psi_{sq} \\ V_{sq} = R_s \cdot I_{sq} + \frac{d\psi_{sq}}{dt} + \omega_s \cdot \psi_{sd} \\ 0 = R_r \cdot I_{rd} + \frac{d\psi_{rd}}{dt} - (\omega_s - \omega_r) \cdot \psi_{rq} \\ 0 = R_r \cdot I_{rq} + \frac{d\psi_{rq}}{dt} + (\omega_s - \omega_r) \cdot \psi_{rd} \end{cases} \quad (2.23)$$

#### 2.5.4.2 Magnetic equations

By applying the Park transformation on the fluxes in the frame  $abc$ , as shown in the following equation:

$$\psi_{dq} = [P(\theta)] \cdot \psi(abc) \quad (2.24)$$

We obtain :

$$\begin{cases} \psi_{sd} = L_s I_{sd} + M I_{rd} \\ \psi_{sq} = L_s I_{sq} + M I_{rq} \\ \psi_{rd} = L_r I_{rd} + M I_{sd} \\ \psi_{rq} = L_r I_{rq} + M I_{sq} \end{cases} \quad (2.25)$$

#### 2.5.4.3 Equation of the electromagnetic torque

The formula for the electromagnetic torque in the  $dq$  frame is given by the equation below:

$$C_{em} = p \frac{3}{2} \frac{M_0}{L_r} (\psi_{rd} I_{sq} - \psi_{rq} I_{sd}) \quad (2.26)$$

#### 2.5.4.4 Mechanical equation

To have a complete model of the machine, it is necessary to introduce the equation of the movement of the machine, commonly called the mechanical equation, which is expressed as following :

$$C_e - C_r = j \frac{d\omega_r}{dt} + f_v \omega_r \quad (2.27)$$

With :

$j$ : Moment of inertia of the rotor.

$f_v$ : Coefficient of viscous friction.

$C_e$ : Electromagnetic couple.

$C_r$ : Resistant torque imposed on the machine shaft.

$\omega_r$ : Rotor speed.

## 2.6 State model

In the case of the asynchronous machine, supplied with voltage, the static voltages are considered as command variable, currents and fluxes as state variables. The asynchronous machine can have different state models. The difference between these models lies in the choice of the state vector  $X$  and in the orientation of the reference frame  $dq$ . The model equations must be in the form of equations of state as such [14]:

$$\dot{X} = AX + BU \quad (2.28)$$

$$Y = CX + DU \quad (2.29)$$

There are different possibilities for the choice of the axis reference, this choice is linked to the study to be carried out, it practically comes down to three references:

1. Referential linked to the rotor:  $\omega = \omega_r$ , this frame of reference is interesting in problems where the speed of rotation is considered constant, for example for the study of the constraints of a short-circuit.
2. Referential related to rotating fields:  $\omega = \omega_s$ , this frame of reference is the only one that does not introduce any simplifications into the formulation of the equations.
3. Referential linked to the stator :  $\theta = \text{constant}$  so  $\omega = 0$ , This frame of reference is chosen when studying variations in the rotational speed, whether or not associated with variations in the supply frequency.

Considering the case of a MAS supplied with voltage, and using the  $dq$  frame of reference related to the rotating field, the possible combinations for the state vector are [14]:

$$X_1 = \begin{pmatrix} i_{ds} \\ i_{qs} \\ i_{dr} \\ i_{qr} \end{pmatrix} \quad X_2 = \begin{pmatrix} \psi_{ds} \\ \psi_{qs} \\ \psi_{dr} \\ \psi_{qr} \end{pmatrix} \quad X_3 = \begin{pmatrix} i_{ds} \\ i_{qs} \\ \psi_{dr} \\ \psi_{qr} \end{pmatrix} \quad (2.30)$$

Using  $(\psi_{ds}, \psi_{qs}, \psi_{dr}, \psi_{qr})$  as state variables, from the equation, we deduce the equation describing the evolution of the flux:

$$\frac{d}{dt} \begin{pmatrix} \psi_{ds} \\ \psi_{qs} \\ \psi_{dr} \\ \psi_{qr} \end{pmatrix} = - \begin{pmatrix} R_s & 0 & 0 & 0 \\ 0 & R_s & 0 & 0 \\ 0 & 0 & R_s & 0 \\ 0 & 0 & 0 & R_s \end{pmatrix} \cdot \begin{pmatrix} i_{ds} \\ i_{qs} \\ \psi_{dr} \\ \psi_{qr} \end{pmatrix} \cdot \begin{pmatrix} 0 & -\frac{d\theta_r}{dt} & 0 & 0 \\ \frac{d\theta_r}{dt} & 0 & 0 & 0 \\ 0 & 0 & 0 & -\frac{d\theta_r}{dt} \\ 0 & 0 & \frac{d\theta_r}{dt} & 0 \end{pmatrix} \cdot \begin{pmatrix} \psi_{ds} \\ \psi_{qs} \\ \psi_{dr} \\ \psi_{qr} \end{pmatrix} + \begin{pmatrix} 1 & 0 \\ 0 & 1 \\ 0 & 0 \\ 0 & 0 \end{pmatrix} \begin{pmatrix} V_{ds} \\ V_{qs} \end{pmatrix} \quad (2.31)$$

which can be rephrased as follows:

$$\frac{d}{dt} \begin{pmatrix} \psi_{ds} \\ \psi_{qs} \\ \psi_{dr} \\ \psi_{qr} \end{pmatrix} = \begin{pmatrix} -\frac{1}{\sigma T_s} & \frac{d\theta_r}{dt} & R_s \frac{1-\sigma}{\sigma M} & 0 \\ -\frac{d\theta_r}{dt} & -\frac{1}{\sigma T_s} & 0 & R_s \frac{1-\sigma}{\sigma M} \\ R_r \frac{1-\sigma}{\sigma M} & 0 & -\frac{1}{\sigma T_r} & \frac{d\theta_s}{dt} \\ 0 & R_r \frac{1-\sigma}{\sigma M} & \frac{d\theta_s}{dt} & -\frac{1}{\sigma T_r} \end{pmatrix} \begin{pmatrix} \psi_{ds} \\ \psi_{qs} \\ \psi_{dr} \\ \psi_{qr} \end{pmatrix} + \begin{pmatrix} 1 & 0 \\ 0 & 1 \\ 0 & 0 \\ 0 & 0 \end{pmatrix} \begin{pmatrix} V_{ds} \\ V_{qs} \end{pmatrix} \quad (2.32)$$

From this we get the equations of following flux:

$$\begin{cases} \frac{d\psi_{sd}}{dt} = -\frac{R_s L_r}{\sigma} \psi_{sd} + \omega_s \psi_{sq} + \frac{R_s M}{\sigma} \psi_{rd} + V_{sd} \\ \frac{d\psi_{sq}}{dt} = -\omega \psi_{sd} - \frac{R_s L_r}{\sigma} \psi_{sq} + \frac{R_s M}{\sigma} \psi_{rq} + V_{sq} \\ \frac{d\psi_{sd}}{dt} = \frac{R_r M}{\sigma} \psi_{sd} - \frac{R_r L_s}{\sigma} \psi_{rd} + \omega_r \psi_{rq} \\ \frac{d\psi_{rq}}{dt} = \frac{R_r M}{\sigma} \psi_{sq} - \omega_r \psi_{rq} - \frac{R_r L_s}{\sigma} \psi_{rq} \end{cases} \quad (2.33)$$

With:

$$\sigma = 1 - \frac{M^2}{L_s L_r} \quad (2.34)$$

$\sigma$ : Total leakage coefficient

## 2.7 Voltage inverter modeling

### 2.7.1 Definition

Inverter is a static converter ensuring the DC-AC conversion. Powered continuously, it periodically modifies the connections between the input and the output and provides alternative output. The variable

output voltage can be obtained by varying the input DC voltage and by keeping the inverter gain constant. On the other hand, if the input voltage is fixed and that it is not controllable, a variable output voltage can be obtained by varying the gain of the inverter. The use of inverters is very extensive in the industry, such as variable speed drives for three-phase motors, emergency power supplies, etc. The appearance of new control techniques allows the inverters to become more efficient. On the other hand, the output voltage form of an inverter must be closer to a sinusoid to which the rate of harmonics is the lowest possible, the latter largely depends on the control technique used. There are several techniques to obtain this variation [15]:

- Pulse width modulation control
- Vector PWM control (SVPWM: Space vector pulse width modulation)

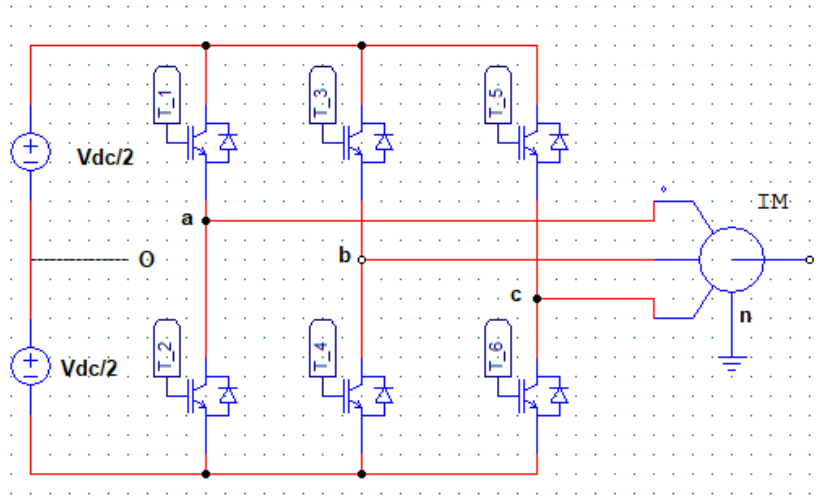


Figure 2.9: Electric model of the inverter

## 2.8 Mathematical model of the inverter

The diagram of the voltage inverter supplying the stator of the asynchronous motor is given by the Figure 2.9, each transistor-diode pair is presented by a single bidirectional switch. The state of the switches, assumed to be perfect, the switches are named as  $S$ , from  $S1$  to  $S6$ . We have six switches and three arms, each arm contains two switches which means:

- If  $S1 = 1$ : is the case where the upper switch is closed and the lower one ( $S2 = 0$ ) is open.
- Or if  $S1 = 0$  is the case where the upper switch is open and the lower one ( $S2 = 1$ ) is closed.

Considering point 'O' as a reference, the output voltage of each phase of inverter is given by [16]:

$$V_X = V_{DC} \left( T_i - \frac{1}{2} \right) \quad (2.35)$$

with:

$$X = a, b, c$$

$$i = 1, 2, 3, 4, 5, 6$$

Let  $n$  be the neutral point of the alternating side (MAS), then we have:

$$\begin{cases} V_{ao} = V_{an} + V_{no} \\ V_{bo} = V_{bn} + V_{no} \\ V_{co} = V_{cn} + V_{no} \end{cases} \quad (2.36)$$

In which:

$$V_{an} + V_{bn} + V_{cn} = 0 \quad (2.37)$$

$$\begin{cases} V_{an} = \frac{1}{3}(V_{ab} - V_{ca}) \\ V_{bn} = \frac{1}{3}(V_{bc} - V_{ab}) \\ V_{cn} = \frac{1}{3}(V_{ca} - V_{bc}) \end{cases} \quad (2.38)$$

The substitution gives us:

$$V_{no} = \frac{1}{3}(V_{ao} + V_{bo} + V_{co}) \quad (2.39)$$

$$\begin{pmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{pmatrix} = \frac{1}{3} \begin{pmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{pmatrix} \begin{pmatrix} V_{ao} \\ V_{bo} \\ V_{co} \end{pmatrix} \quad (2.40)$$

The instantaneous equations of phase-to-neutral voltages as a function of the command quantities:

$$\begin{pmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{pmatrix} = \frac{V_{DC}}{3} \begin{pmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{pmatrix} \begin{pmatrix} S_a \\ S_b \\ S_c \end{pmatrix} \quad (2.41)$$

Therefore, the voltage inverter can be modeled by a matrix  $[T]$  ensuring the passage DC-AC.

$$[V_{ac}] = [T][V_{DC}] \quad (2.42)$$

With:

$$[V_{ac}] = [V_{an} V_{bn} V_{cn}][T]$$

$$[V_{DC}] = [V_{ao} V_{bo} V_{co}][T]$$

So, for each arm, there are two independent states. These two states can be considered as Boolean quantities. The transfer matrix is as follows:

$$[T] = \begin{pmatrix} \frac{2}{3} & -\frac{1}{3} & -\frac{1}{3} \\ -\frac{1}{3} & \frac{2}{3} & -\frac{1}{3} \\ -\frac{1}{3} & -\frac{1}{3} & \frac{2}{3} \end{pmatrix} \quad (2.43)$$

## 2.9 Principle of control by pulse width modulation

### 2.9.1 Definition

Pulse width modulation (PWM) is a powerful technique for controlling analog circuits with a microcontroller's digital outputs. PWM is used in many applications, ranging from communications to power control and conversion. For example, the PWM is commonly used to control the speed of electric motors, the brightness of lights, in ultrasonic cleaning applications, and many more [16].

### 2.9.2 PWM control

This technique is based on the comparison of a reference signal called modulator of amplitude  $A$  and frequency  $f$ , with a signal called carrier of amplitude  $A_p$  and very high frequency  $f_p$  [16].

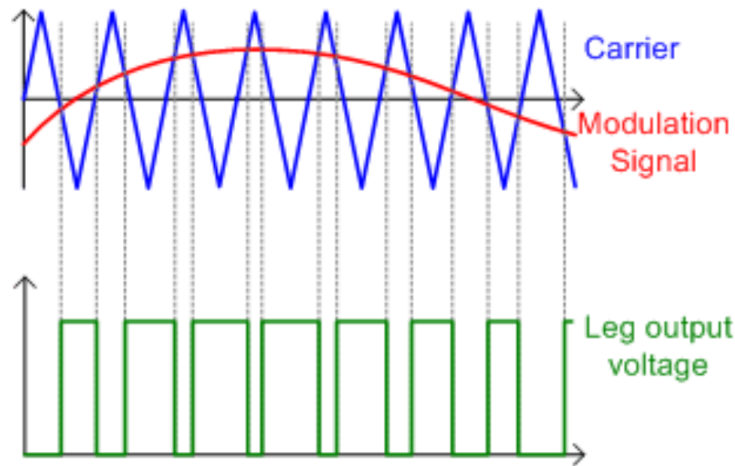


Figure 2.10: PWM control

### 2.9.2.1 Properties of PWM control

If the reference is sinusoidal :

The modulation index  $I_m$  equal to the report of the modulation frequency (carrier)  $f_p$  on the (modulating) reference frequency  $f_m$ .

$$I_m = \frac{f_p}{f_m}$$

The modulation rate  $T_m$  equal to the ratio of the amplitude of the modulating  $A_m$  to that of the carrier  $A_p$ .

$$T_m = \frac{A_m}{A_p}$$

The other properties of this technique are:

1. Current harmonics :

Current harmonics are the source of joule losses which represent a large part of the losses of the machine, they do not allow to evaluate the performances of a PWM, since they also depend on the impedances of the machine. To eliminate this dependence, we introduce the harmonic distortion factor which allows to characterize the quality of a PWM sequence in terms of minimization current harmonic distortion, regardless of the load connected to it [15].

2. Spectrum of current harmonics:

The typical harmonic spectrum of constant switching frequency PWMs presents lines of significant amplitude around this frequency, and its multiple. This leads to acoustic noise problems, which can be amplified by mechanical resonance phenomena. Analysis by FFT (Fast Fourier transformation) of the current or voltage gives its harmonic spectrum, which is a more detailed characteristic than the global harmonic distortion factor. To evaluate and compare PWM performance, the current harmonic spectrum turns out to be the main criterion.

3. Switching losses:

They depend on the voltage  $U_0$  of the contained bus, the current in the load, and the switching frequency  $f_c$ , this is why at high power, the number of switchings per period of the fundamental is weak. They also depend, for certain PWMs, of the power factor of the load.

## 4. Torque ripple:

The electromagnetic torque ripples of a machine are created by a sequence of PWM, such that certain applications impose an undulation of the low torque, because there are PWMs optimized in this direction.

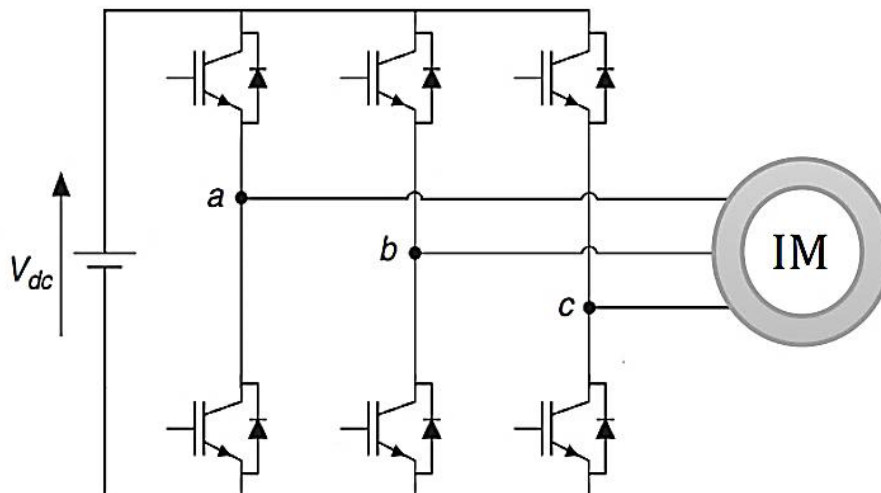


Figure 2.11: Voltage vectors for the eight inverter states

## 2.10 Simulation of the asynchronous machine model

Before integrating the induction machine model (Of the PSIM software platform ) into closed loop speed control, it will first be simulated in an open loop, consisting of an induction motor, a two-level three-phase inverter and a DC source. The inverter switches signals are generated from a simplified C block. First, the IM will be simulated at no-load, where the frequency and magnitude of the reference voltage will be varied, then the motor will run under load which will take different values while keeping the reference voltage fixed.

## 2.11 Simulation results

As mentioned previously, we start by simulating the IM at no-load condition. For the reference voltage, the amplitude is chosen at 0.9V for the first three seconds, then it changes to 0.7V for the last three seconds. While for the frequency of the reference voltage, from 0s to 2s it is chosen at 50Hz, then from 2s to 4s, it goes to 25Hz, while for the last 2s, it goes to 40Hz.

The output current and speed of the IM obtained from this simulation are presented successively in Figure 2.13 and Figure 2.14.

For the on-load scenario, the amplitude and frequency of the reference voltage are successively 0.8V and 50Hz . Meanwhile, the load is chosen to be 10Nm during the first 2 seconds and will be shifted to 20Nm for the two next seconds then will decreased to 5Nm during the last two seconds.

The obtained output current and speed are presented successively in Figure 2.15 and Figure 2.16.

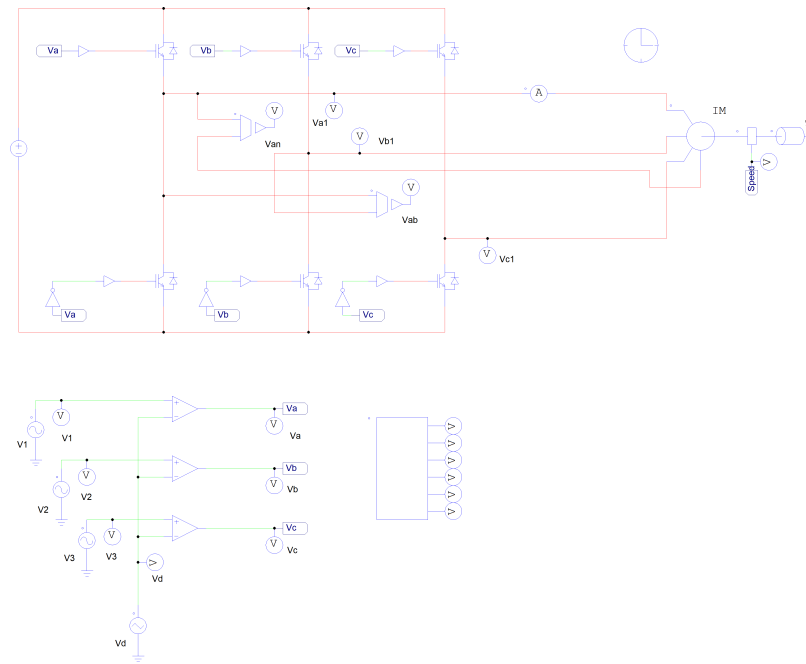


Figure 2.12: Block diagram of the open-loop circuit control

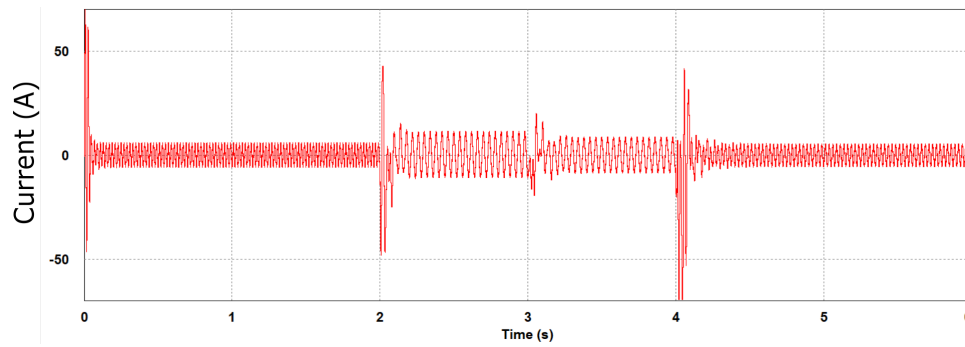


Figure 2.13: No-load open-loop current

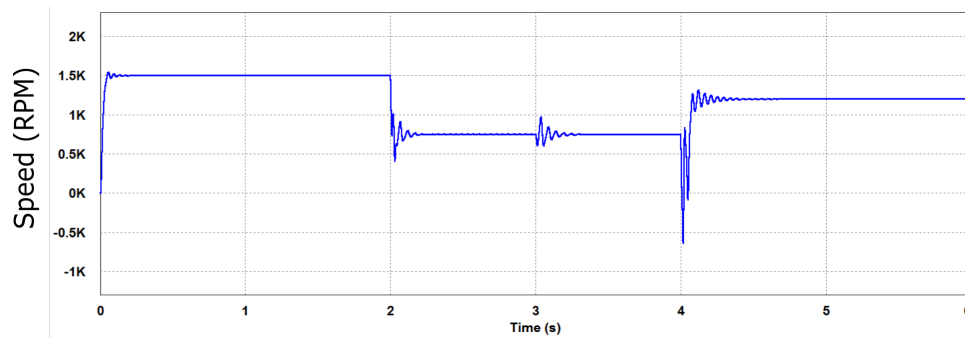


Figure 2.14: No-load open-loop output speed

## 2.12 Conclusion

In this chapter, we have provided a complete and detailed definition of the motor Asynchronous and its components and principle of operation and Its various characteristics. We moved on to modeling at the

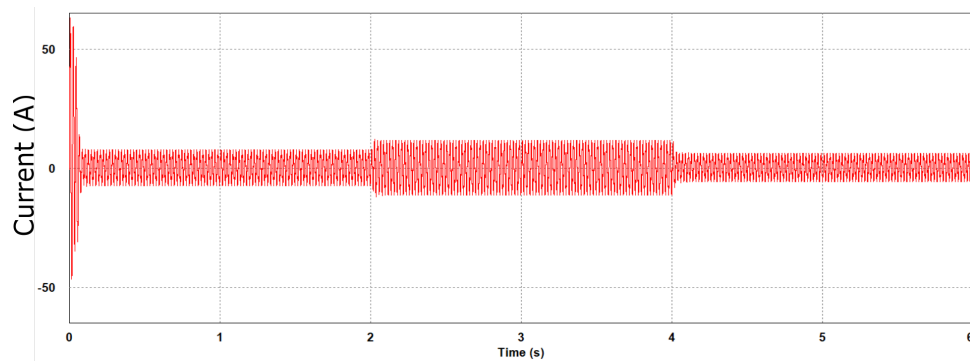


Figure 2.15: On-load open-loop current

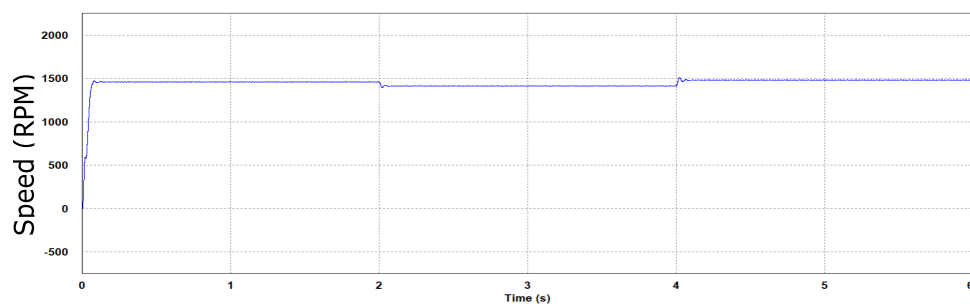


Figure 2.16: On-load open-loop output speed

level abc Then we introduced the various equations of this machine in the two-phase plane in Using the frame of reference dq associated with the rotating field.we also mention the PWM technique . In the second part of this chapter, the results were simulated in PSIM model, Which allowed us to compare the results of the sinsoidal and the carrier signal they wiche shows that our simulation is work in perfect case .

### 3.1 Introduction

The control of asynchronous machines is a very important field of research, which has been very active for the last decades, and which is gaining more and more importance owing to its place in the world of electric cars today.

Due to the coupled and non-linear nature of the induction machine, its speed and torque cannot be controlled directly and separately as in the case of DC motors. For this reason, various methods have been proposed in the literature to control the latter.

In this chapter, we will study the most common techniques used to control the speed of the asynchronous motor and give more consideration to The Direct Torque Control (DTC) technique that we will use in this work. To confirm to effectiveness of the DTC technique in the induction motor speed control for electric vehicles, we will implement the control algorithm in the DSP TMS320F28355 and use the New European Driving Cycle (NEDC) as speed reference because it covers the different driving scenarios. The obtained simulation results will be given and discussed at the end of the chapter.

### 3.2 Induction motor speed control techniques

In the literature, different control techniques have been applied to control the speed of the induction motor, the most used of them are:

#### 3.2.1 Scalar control

The scalar control is the oldest and simplest of the control laws of a asynchronous machine. It is mainly used for applications requiring only average static or dynamic performance. Nowadays, thanks to advances in power electronics, many drives use this control mode. We found mainly for industrial applications of pumping, air conditioning, ventilation.

The principle of this method is quite rustic. It consists in imposing at the terminals of the armature of the machine, the module of the voltage or the current as well as the pulsation. Multiple commands scalars exist depending on whether one acts on the current or on the voltage. They mainly depend on

the topology of the actuator used (Voltage or current inverter). In the power supply voltage, inverters provide voltages whose shape and amplitude can be considered load independent. On the other hand, in the power supply, the currents supplied have shapes and amplitudes influenced by the nature of the load. The change in speed is obtained by the variation of the stator pulsation which is generated directly by the regulator [17].

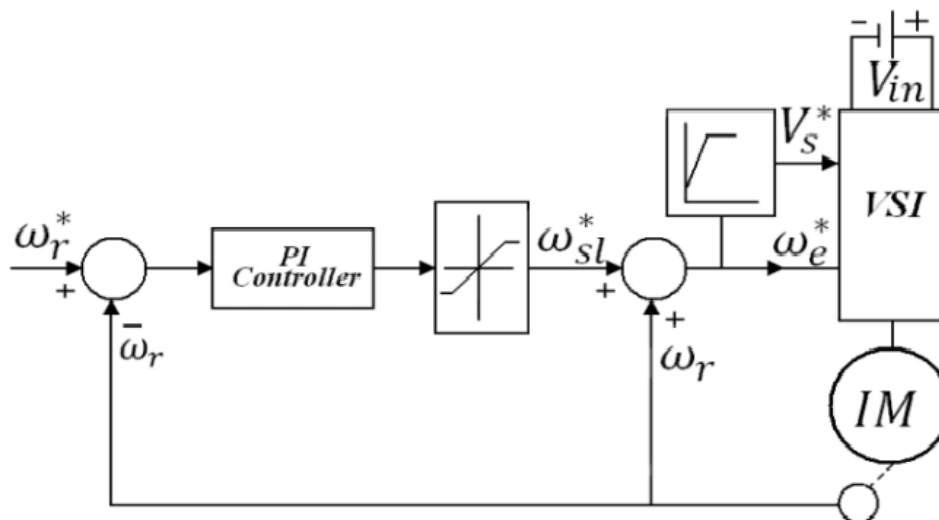


Figure 3.1: The scalar control

This control method is based on the steady-state machine model. It can operate in open loop also (i.e. without speed feedback), however, it provides poor speed regulation which is become depended on the applied external load. The main drawbacks of this technique are the unsatisfied speed accuracy. In addition, the sluggish dynamic response which produce slow torque response. Since the control design is maintained in the steady state, the magnitude of the stator flux is not controlled during the transient and the machine torque cannot respond quickly [17].

### 3.2.2 Vector control

Introduced by Blaschke in 1972, it constitutes a historic revolution for the control of the asynchronous machine. This technique consists of bringing the behavior of the asynchronous machine, from the speed variation point of view, to that of the direct current motor by performing a decoupling between the flux and the electromagnetic torque. This control strategy uses two control loops to simultaneously control torque and flux, it therefore ensures very good accuracy for torque and speed control.

However, the main drawbacks of this technique compared to the scalar control technique are the complex computation and the requirement of the good identification of the motor parameters. It is also very sensitive to parameters variations, in particular to that of the rotor resistance whose value changes significantly with the temperature, Therefore, any difference between the parameters used by the algorithm and the actual motor parameters results in errors in the flux and torque output values which will increase machine losses and decrease the performance of the system to be controlled.

### 3.2.3 Direct Torque Control or “DTC” Technique

The technique of direct torque control (Direct Torque Control or “DTC”) is introduced in 1985 by TAKAHASHI. Several works have allowed a rigorous modeling of this approach. It allows to calculate

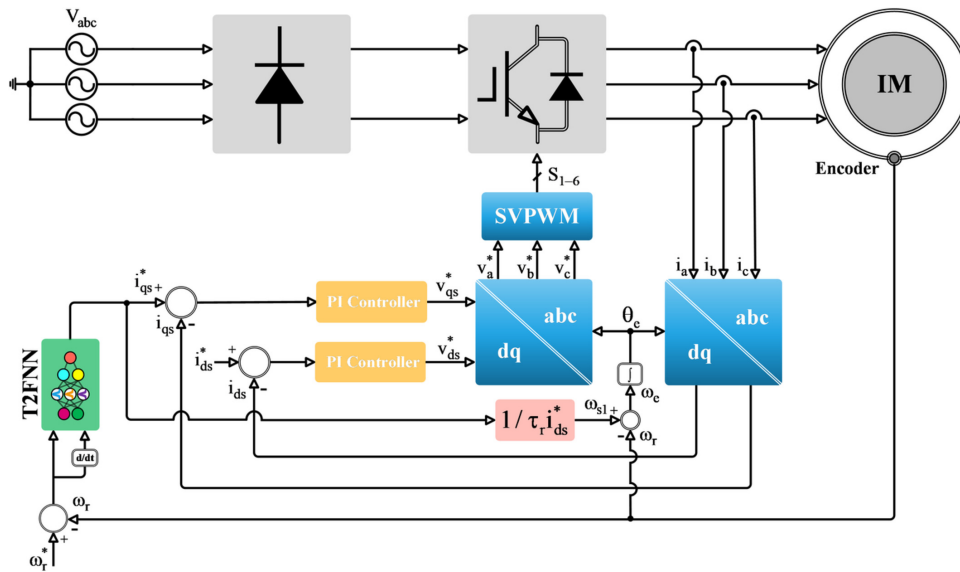


Figure 3.2: The Vector control

the quantities of control which are the stator flux and the electromagnetic torque from the measurements of the stator currents without the use of mechanical sensors. DTC direct torque control methods are allowed to directly control the closing or opening of the inverter switches from the pre-calculated values of the stator flux and torque. Switch state changes are related to the evolution of the electromagnetic states of the engine. They are no longer ordered from voltage and frequency instructions given to the close control of an inverter at pulse width modulation. The control of the switches aims to give the vector representing the flux stator the direction determined by the setpoints [18].

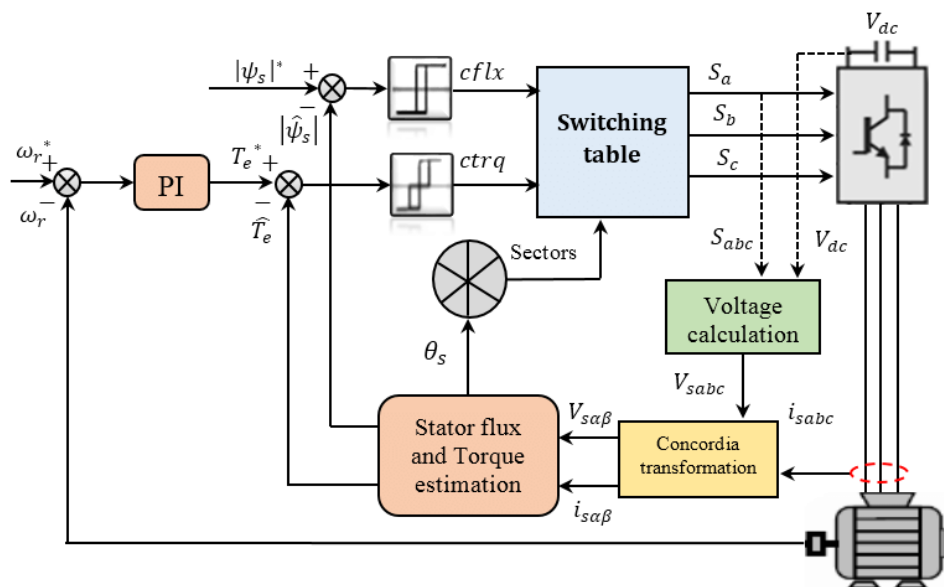


Figure 3.3: The control scheme of Direct torque control

### 3.2.3.1 Principle of the DTC command

The objective of the DTC is the direct regulation of the torque of the machine, by the application of the different voltage vectors of the inverter, which determines its state. The variables controlled are: The

stator flux and the electromagnetic torque which are usually controlled by hysteresis regulators. It is a question of maintaining the quantities of stator flux and electromagnetic torque within these hysteresis bands. The output of these regulators determine the optimal inverter voltage vector to apply to each switching time. In a DTC command, it is preferable to work with a high calculation frequency to reduce torque oscillations caused by hysteresis controllers.

The control scheme is very often used in the industry in low and medium power applications. The main advantages of DTC are summarized in its fast dynamic of the drive, the absence of coordinate transformations and current control loops and its universal structure, where the switching table DTC can be used for all AC machines. In the other hand, the main disadvantages of DTC are the variable switching frequency, high torque ripples and high switching losses [19].

### 3.3 Model of induction motor dedicated for Direct Torque Control

The dynamic equations model of the induction motor which is dedicated for direct torque control is expressed below in Eq (3.1) and Eq (3.2). It can be written in the stator fixed reference frame  $\alpha, \beta$  (stationary frame) by assuming the stator current and the stator flux as state variables.

$$\begin{cases} \frac{di_{s\alpha}}{dt} = -\left(\frac{R_s}{\sigma L_s} + \frac{R_r}{\sigma L_r}\right)i_{s\alpha} - \omega_r i_{s\beta} + \frac{R_s}{\sigma L_s L_r} \psi_{s\alpha} + \frac{\omega_r}{\sigma L_r} \psi_{s\beta} + \frac{1}{\sigma L_s} u_{s\alpha} \\ \frac{di_{s\beta}}{dt} = -\left(\frac{R_s}{\sigma L_s} + \frac{R_r}{\sigma L_r}\right)i_{s\beta} - \omega_r i_{s\alpha} + \frac{R_s}{\sigma L_s L_r} \psi_{s\beta} + \frac{\omega_r}{\sigma L_r} \psi_{s\alpha} + \frac{1}{\sigma L_s} u_{s\beta} \end{cases} \quad (3.1)$$

$$\begin{cases} \frac{d\psi_{s\alpha}}{dt} = u_{s\alpha} - R_s i_{s\alpha} \\ \frac{d\psi_{s\beta}}{dt} = u_{s\beta} - R_s i_{s\beta} \end{cases} \quad (3.2)$$

With :

- $i_{s\alpha}, i_{s\beta}$  : are stator current components
- $\psi_{s\alpha}, \psi_{s\beta}$  : are stator flux components
- $R_s, R_r$ : are stator and rotor resistance
- $L_s, L_r$ : are stator and rotor inductance
- $\sigma = 1 - \frac{M_s r}{L_s L_r}$  : is the Blondel's coefficient
- $M_{sr}$ : is the mutual stator-rotor inductance

### 3.4 Two-Level Voltage Source Inverter (VSI) Model

Before moving to the algorithm of basic DTC, we should represent the model of two-level voltage inverter that we already present in The Figure 2.9 which shows a simplified scheme of the two-level three-phase topology of the voltage source inverter. The induction motor is supposed as a star-connected three phase balanced load.

### 3.5 Control of stator flux and electromagnetic torque

#### 3.5.1 Control of stator flux

The stator flux equation of the IM can be expressed as follows [19]:

$$\frac{d\psi_s}{dt} = V_s - R_s i_s \quad (3.3)$$

$$\psi_s(t) = \int_0^{T_z} (V_s - R_s i_s) dt + \psi_s(0) \quad (3.4)$$

With :

$\psi_s(0)$ :the flux vector at the instant  $t=0s$

By applying a non-zero vector in  $Tz$  sampling period, we can neglect the stator resistance voltage drop  $R_s i_s$  compared to  $Vs$  for high speed regions. Then Eq (3.4) can be written as:

$$\psi_s(t) = V_s T_z + \psi_s(0) \quad (3.5)$$

The relation between the stator voltage and the stator flux change can be established as:

$$\Delta\psi_s = \psi_s(t) - \psi_s(0) = V_s T_z \quad (3.6)$$

The Eq (3.6) means that the stator flux can be changed by the application of stator voltage during a time  $Tz$ . The stator flux vectors extremity moves in direction given by the voltage vector and making a circular trajectory (Figure 3.4).

Two-level hysteresis comparator is used for flux regulation. It allows to drop easily the flux vector

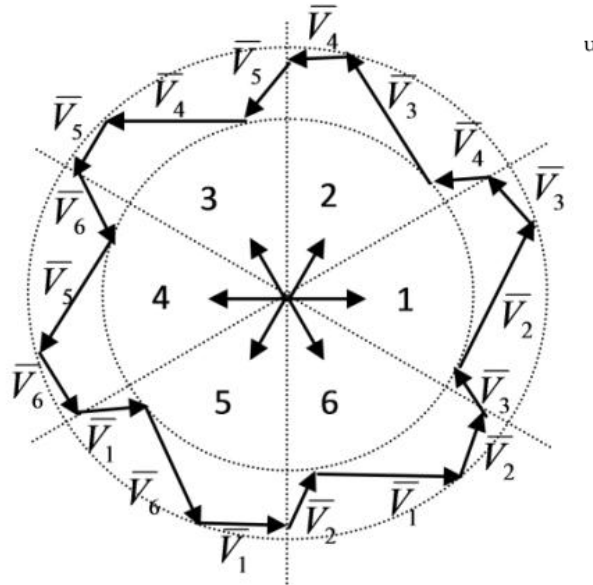


Figure 3.4: Evolution of stator flux vector in the complex plan.

extremity within the limits of the two concentric circles with close radius, as shown in Figure 3.6. The choice of the hysteresis bandwidth  $h_{\psi_s}$  depends on the switching frequency of the inverter.

The logical outputs of the flux controller are defined as:

$$\text{if } (\Delta\psi_s \geq h_{\psi_s}) \text{ cflx} = 1$$

$$\text{if } (\Delta\psi_s \leq -h_{\psi_s}) \text{ cflx} = 0$$

With :

$h_{\psi_s}$ : is hysteresis band of stator flux

The stator flux error is defined by:

$$\Delta\psi_s = |\psi_s^*| - |\psi_s| \quad (3.7)$$

### 3.5.2 Control of electromagnetic torque

Considering that the rotor flux vector is invariant. The torque of induction motor can be expressed in terms of stator and rotor flux vectors as follows:

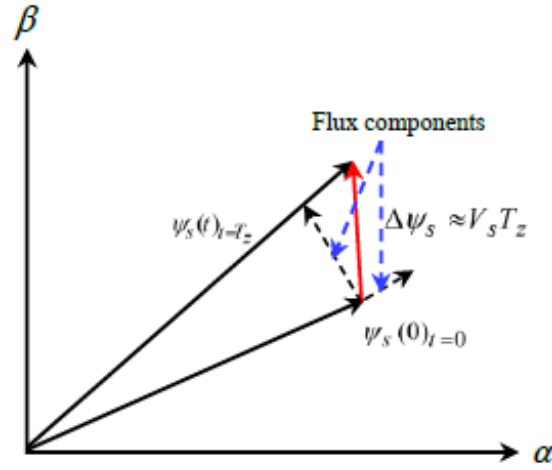


Figure 3.5: Evolution of stator flux vector in the complex plan.

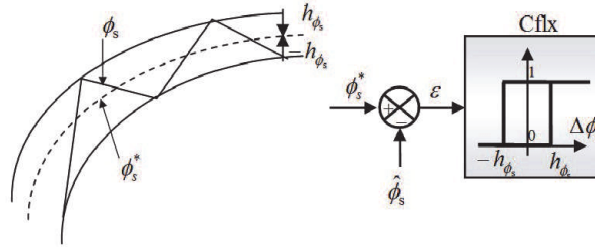


Figure 3.6: Tow-level hysteresis comparator for stator flux control.

$$T_e = p \frac{M_{sr}}{\sigma L_s L_r} \psi_s \psi_r \quad (3.8)$$

$$|T_e| = p \frac{M_{sr}}{\sigma L_s L_r} |\psi_s| |\psi_r| \sin(\sigma) \quad (3.9)$$

with:

$p$ : the number of poles pairs.

$\psi_s$ ,  $\psi_r$ : stator and rotor flux vectors.

$\sigma$ : angle between the stator and rotor flux vectors.

The electromagnetic torque is controlled by the stator and rotor flux amplitudes. If those quantities are maintaining constant, the torque can be controlled by adjusting the load angle  $\sigma$ . The torque regulation can be realized using three-level hysteresis comparator (Figure 3.7). It allows to control the motor in both rotation senses. The three-level comparator can be used for one rotation sense. The logical outputs of the flux controller are defined as:

$$\text{if } (\Delta T_e \geq h_{\psi_s}) \text{ } ctrq = 1$$

$$\text{if } (h_{\psi_s} \leq \Delta T_e \leq -h_{\psi_s}) \text{ } ctrq = 0$$

$$\text{if } (\Delta T_e \leq -h_{\psi_s}) \text{ } ctrq = -1$$

with :

$h_{T_e}$ : is hysteresis band of torque.

The torque error is defined by :

$$\Delta T_e = |T_e^*| - |T_e| \quad (3.10)$$

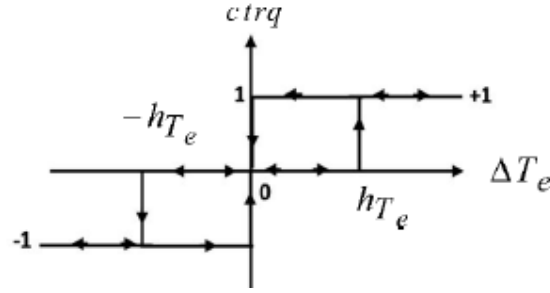


Figure 3.7: Three-level hysteresis comparator for stator flux control.

## 3.6 Estimation of stator flux and electromagnetic torque

### 3.6.1 Stator flux estimation

The stator flux components can be expressed using stator voltages and currents in the stationary reference frame  $\alpha, \beta$  by:

$$\begin{cases} \psi_{s\alpha} = \int_0^{T_z} (V_{s\alpha} - R_s i_{s\alpha}) dt \\ \psi_{s\beta} = \int_0^{T_z} (V_{s\beta} - R_s i_{s\beta}) dt \end{cases} \quad (3.11)$$

The stator flux magnitude and flux angle can be computed as:

$$|\psi_s| = \sqrt{\psi_{s\alpha}^2 + \psi_{s\beta}^2} \quad (3.12)$$

$$\theta_s = \tan^{-1}(\psi_{s\beta}/\psi_{s\alpha}) \quad (3.13)$$

### 3.6.2 Electromagnetic torque estimation

The torque formula is expressed as following:

$$T_e = p(\psi_{s\alpha} i_{s\beta} - \psi_{s\beta} i_{s\alpha}) \quad (3.14)$$

## 3.7 Sectors switching table

The choice of voltage vector is not only depending on the output of hysteresis controllers, but on the position of stator flux vector also. Thus, the circular stator flux vector trajectory will be divided into six symmetrical sectors [20].

The resulting look-up table for DTC which was proposed by Takahashi is presented in Table 3.1.

## 3.8 Speed regulation in DTC strategy

DTC strategy has the ability to operate even without a speed regulation loop, so it does not require any information about rotor speed to achieve an adjustable speed control, a speed controller is necessary to have a speed regulation and to generate the reference of electromagnetic torque. The proportional-integral (PI) controller is used for the regulation. It is performed by comparing the speed reference signal to the actual measured speed value. Then the comparison error becomes the input of the PI controller. The used PI controller in the outer speed loop is the anti-windup controller. It allows to enhance speed

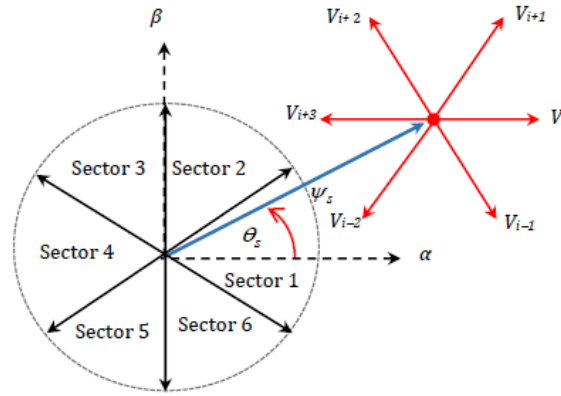


Figure 3.8: Voltage vector selection when the stator flux vector is located in sector i

Error	Sectors	I	II	III	IV	V	VI
$cflx = 1$	$ctrq = 1$	$V_2$	$V_3$	$V_4$	$V_5$	$V_6$	$V_1$
	$ctrq = 0$	$V_7$	$V_0$	$V_7$	$V_0$	$V_7$	$V_0$
	$ctrq = -1$	$V_6$	$V_1$	$V_2$	$V_3$	$V_4$	$V_5$
$cflx = 0$	$ctrq = 1$	$V_3$	$V_4$	$V_5$	$V_6$	$V_1$	$V_2$
	$ctrq = 0$	$V_0$	$V_7$	$V_0$	$V_7$	$V_0$	$V_7$
	$ctrq = -1$	$V_5$	$V_6$	$V_1$	$V_2$	$V_3$	$V_4$

Table 3.1: Look-up table for basic direct torque control.

control performance by canceling the windup phenomenon which is caused by the saturation of the pure integrator [12].

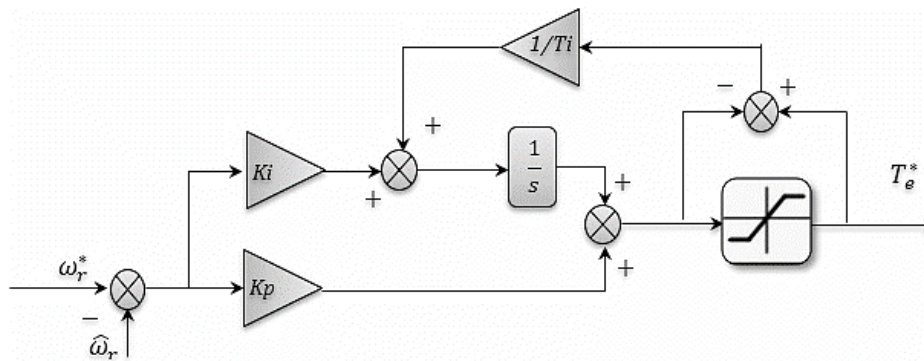


Figure 3.9: Speed anti-windup PI controller.

This strategy consists on the correction of the integral action based on the difference between the control signal and the saturation limit. The difference value is passed through a gain block (tracking time constant  $Ti$ ) before arriving as feedback to the integrator [12].

### 3.9 Simulation Results

To confirm the effectiveness of DTC technique in the speed control of induction motor for electric vehicle, a simulation test is carried out on the PSIM software platform with induction motor of 4kW, the resistive torque is chosen so as to mimic as much as possible the torque exerted on the induction motor when it is in the real electric vehicle. In the same principle of simulating the motor operation in an environment close to that of the EV, the speed reference is given similarly to the New European Driving Cycle (NEDC), which is designed to assess the emission levels of the car engines and fuel economy in passenger cars. As shown in Figure 3.10, it consists of four repeated ECE-15 urban driving cycles (UDC) and one Extra-Urban driving cycle (EUDC). Meanwhile, since it is impossible to simulate the whole driving cycle which lasts 1200s and operates at real speed with a maximum of 120km/h, the simulation time is reduced to 120s while the speed is adopted to the IM speed with a maximum of 1500 rpm, so the resulting new NEDC which suits our work keeps the shape of the real NEDC is depicted in the Figure 3.11.

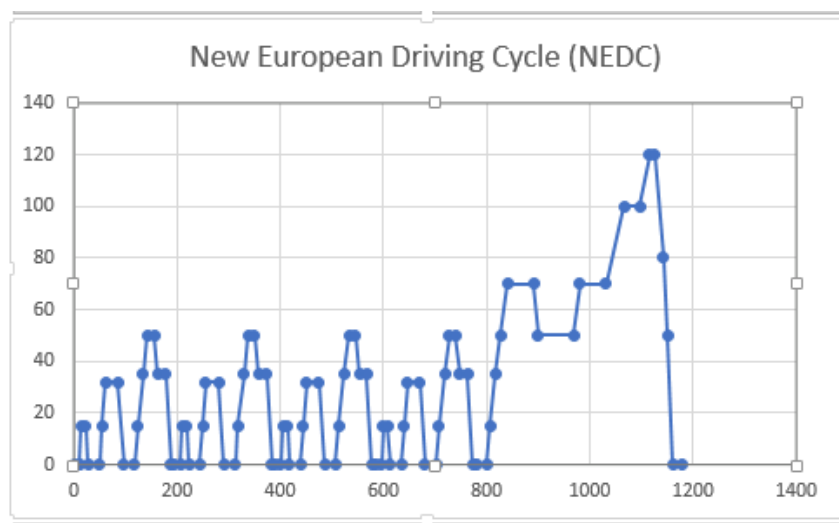


Figure 3.10: New European Driving Cycle (NEDC)

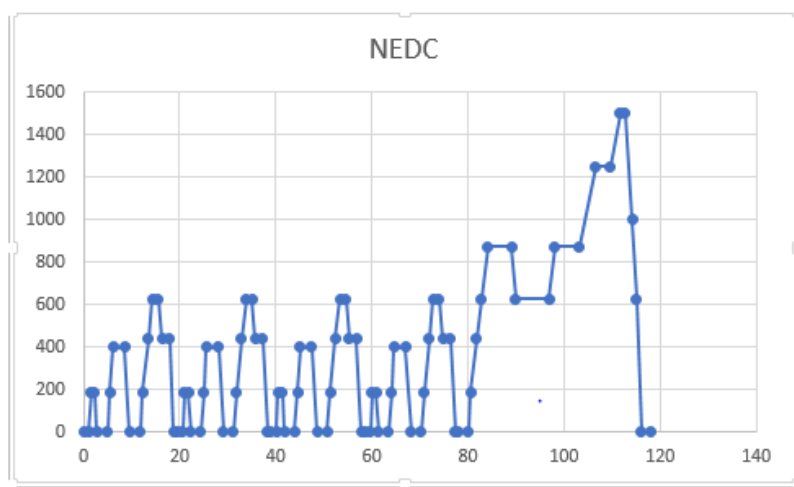


Figure 3.11: The reference speed adopted from the NEDC driving cycle

The simulation is done in two stages:

### 3.9.1 Simulation using the PSIM C block

In this first step, the simulation is performed by implementing the DTC algorithm in the PSIM C block as shown in Figure 3.12. The obtained results are shown in the Figures 3.13-3.16.

Figure 3.13 depicts speed and speed reference with zoom 3.13. As it can be seen only one urban driving cycle is simulated as it is similar to other UDCs, on one side, on the other side, once a good result is achieved for the UDC, there is no doubt that a similar or better result will be obtained for the EUDC because its shape is more easier for the control loop. The Figure also shows that the speed wave is in complete accordance with the speed reference wave, which confirms the ability and the efficiency of the DTC technique in controlling the speed of the motor of the electric vehicle.

Figure 3.14 shows the output current, it has sinusoidal shape and its amplitude follows the value of the resistant torque depicts in Figure 3.15 because the current value is increased and decreased according to the applied torque.

The obtained electromagnetic torque shown in Figure 3.16 is also in accordance with the imposed resistant torque shown in Figure 3.15. While the flux is imposed  $1wb$  as shown in Figure 3.17.

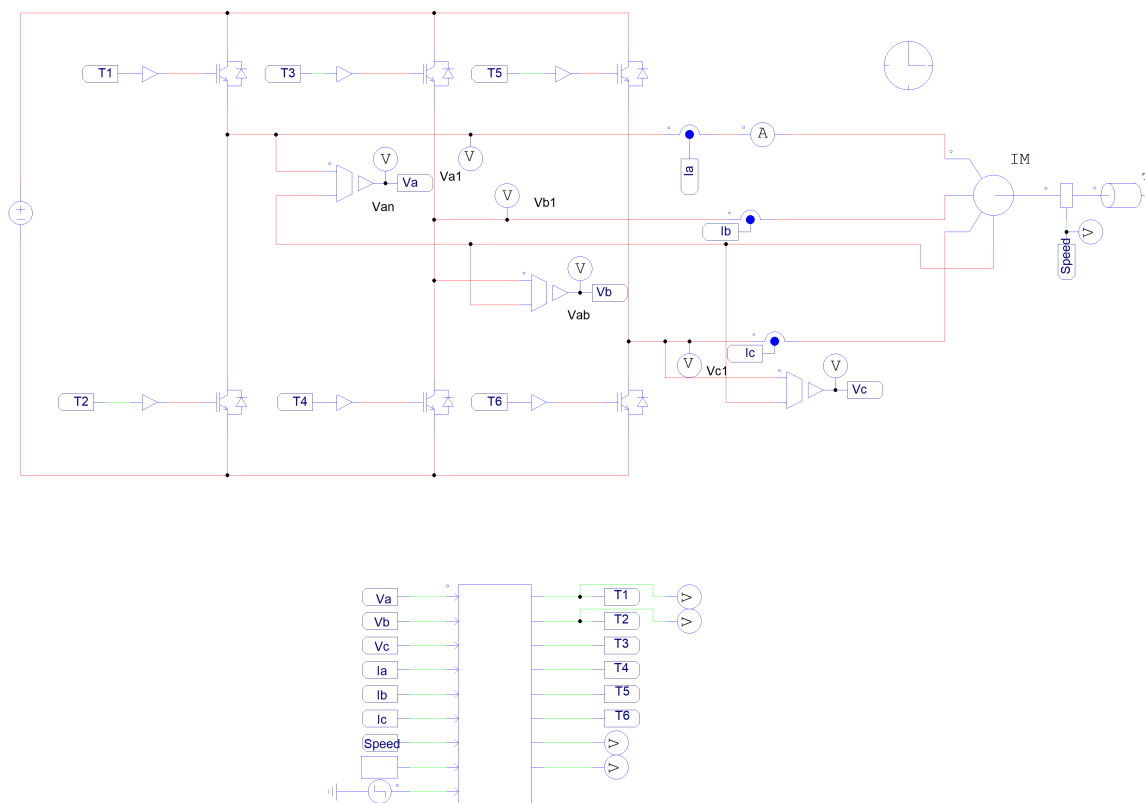


Figure 3.12: Block diagram of simulation circuit using the PSIM C bloc

### 3.9.2 Simulation using DSP TMS320F28335

In the second step, the simulation is carried out by implanting the DTC algorithm in the DSP TMS320F28335 as shown in Figure 3.18. The speed reference is kept as in the first simulation step (Figure 3.18), only the resistant torque is modified to expose regulation algorithm to another challenging resistant torque and see how it will react.

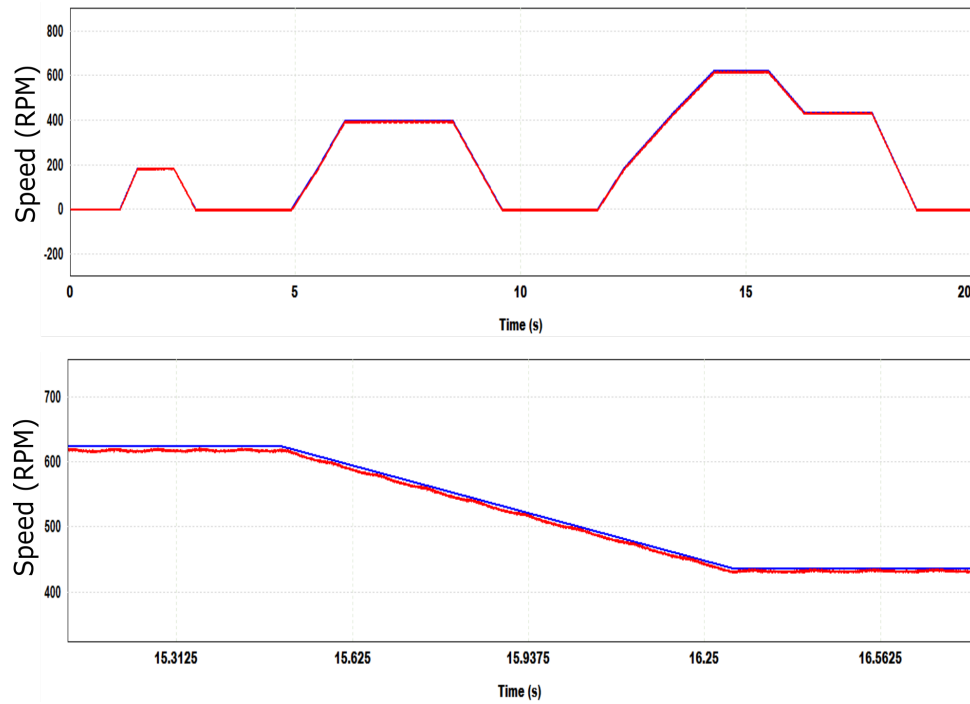


Figure 3.13: Speed and speed reference with zoom [Rpm]

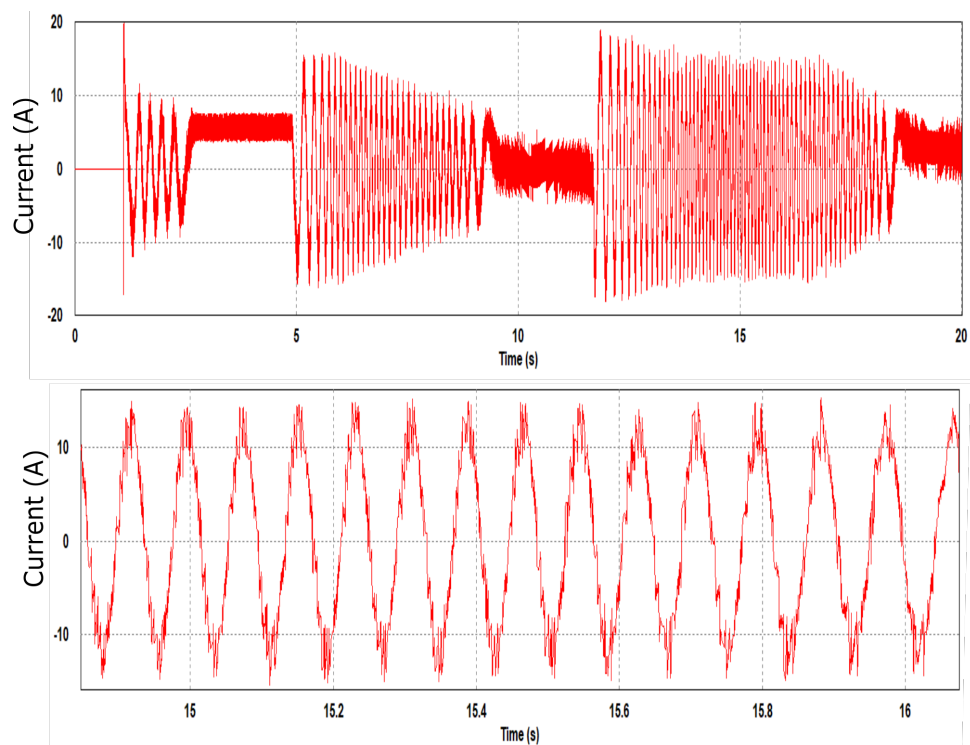


Figure 3.14: Output current with zoom [A]

Figure 3.19 shows how the speed and the speed reference waves are superposed on each other, which confirms once again the effectiveness of the DTC algorithm in the speed control of the induction motor intended for the electric vehicle. For the torque, it can be seen in figure 3.20 that the amplitude of the output current also takes the shape of the resistant torque.

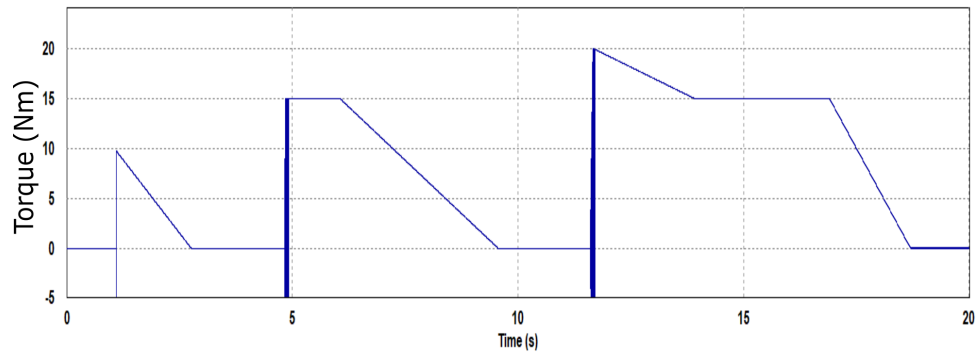


Figure 3.15: Resistant torque [Nm]

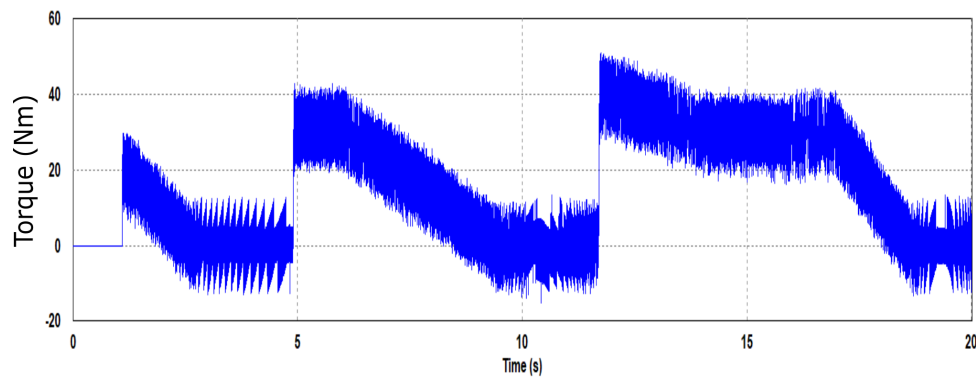


Figure 3.16: Electromagnetic torque [Nm]

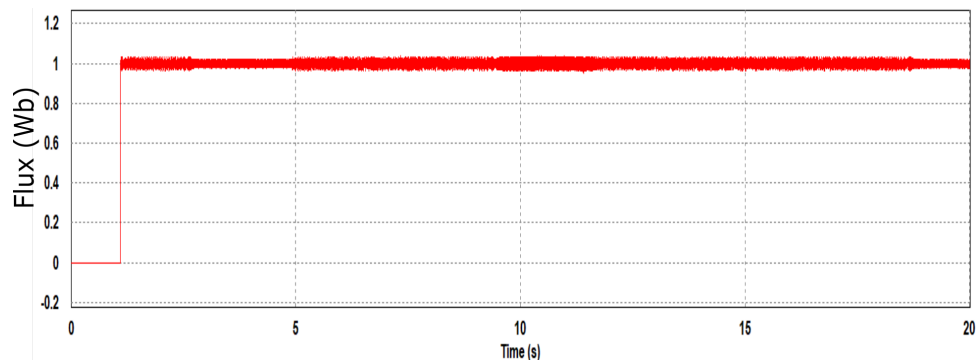


Figure 3.17: Flux [wb]

### 3.9.3 Simulation using Processor-in-the-loop (PIL)

To fully evaluate the effectiveness of DTC algorithm in electric vehicle induction motor speed control, it should be tested in a real experiment, but since the experiment setup was not ready during the realization of this work, we turned to the processor in the loop (PIL) process, which allows to carry out a realistic test by implementing the algorithm in the real DSP and while for the rest of the circuit (inverter, induction motor), we continue to use the PSIM models. The inverter switches control signals are sent from the DSP to the computer via a USB cable.

The PIL results were almost the same as the simulated ones. However, since we were unable to run the simulation for the entire USC, we only presented those obtained using the DSP TMS320F28335 of the PSIM software platform.

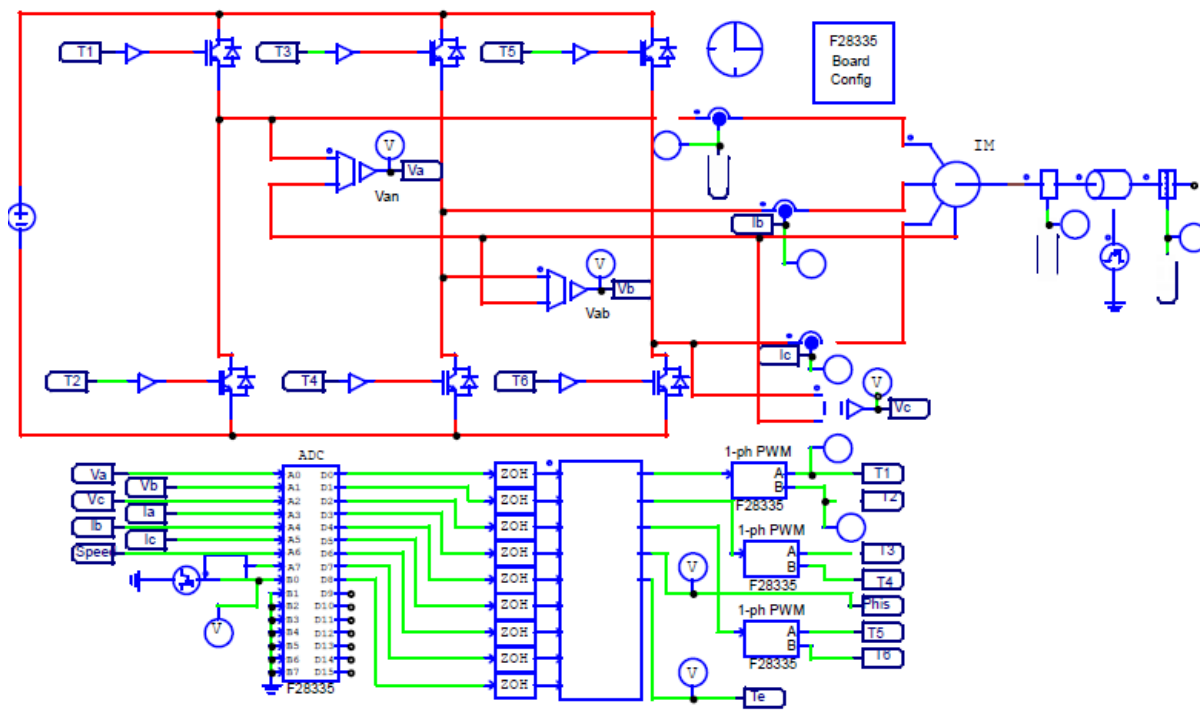


Figure 3.18: Block diagram of simulation circuit using the DSP TMS320F28335

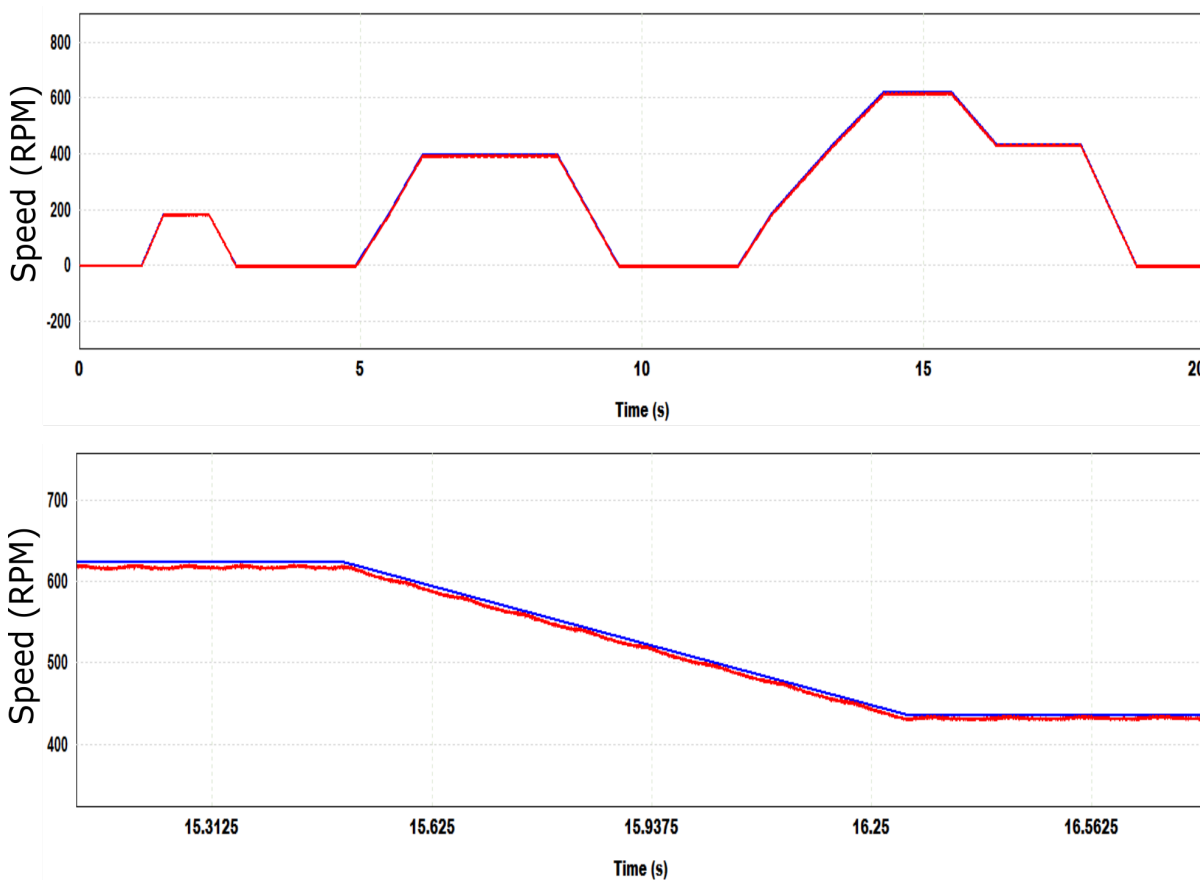


Figure 3.19: Speed and speed reference with zoom [Rpm]

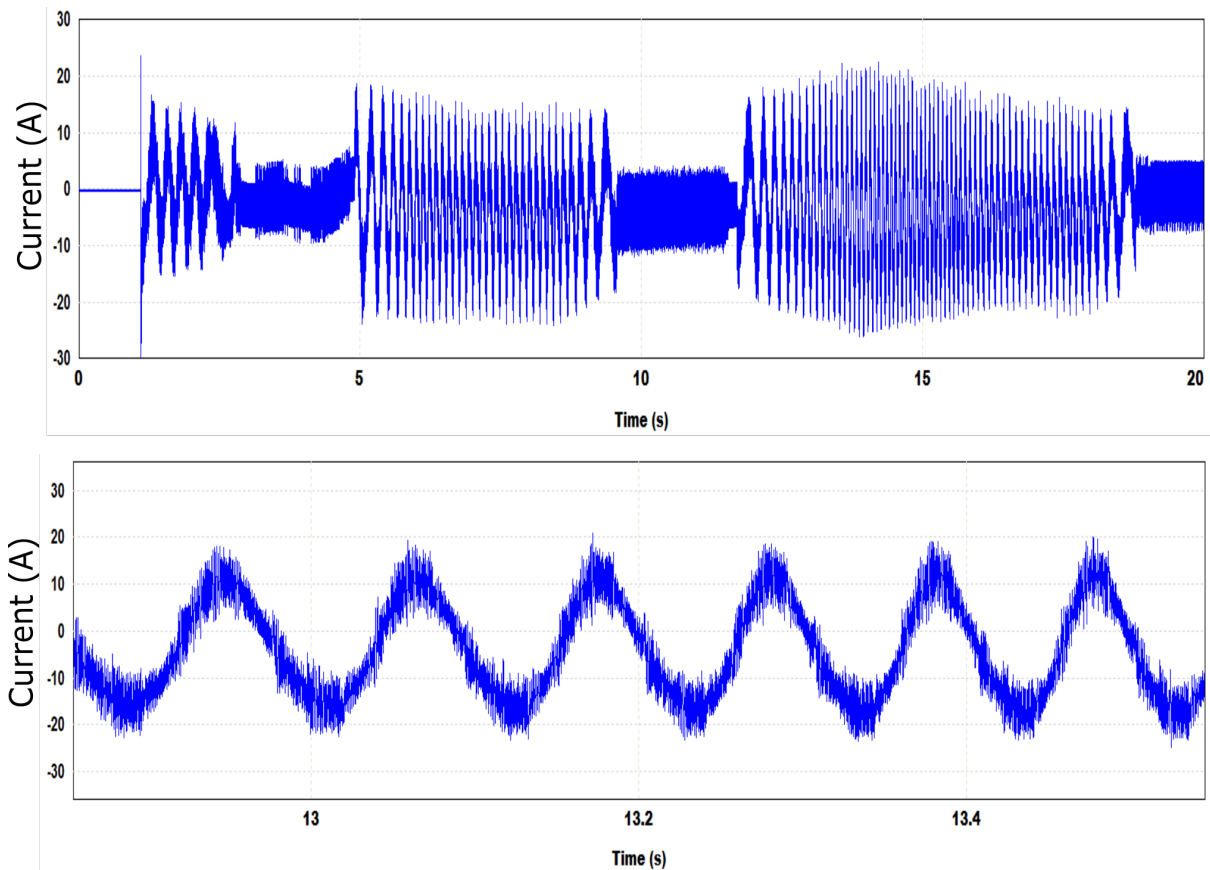


Figure 3.20: Out put current with zoom [A]

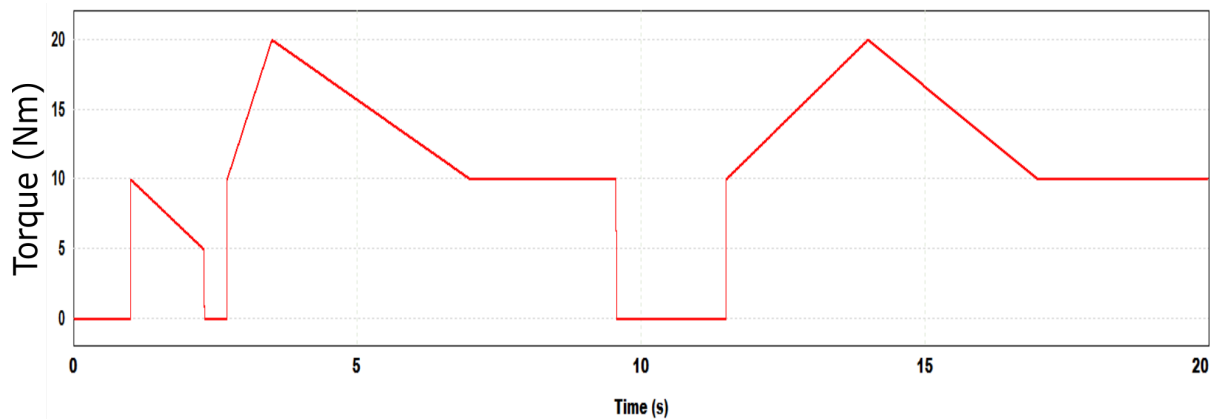


Figure 3.21: Resistant torque[Nm]

### 3.10 Conclusion

In this chapter, the most used techniques in asynchronous motor speed control are briefly presented, then a detailed explanation was given to the DTC technique as it is the technique used in this work. The second part of the chapter was devoted to the simulation process and results. In the first part of the simulation, the DTC algorithm was implemented in the C block, while in the second part, it was implemented in the DSP TMS320F28335 . The results of both parts were given and discussed.

## GENERAL CONCLUSION

This dissertation deals with the speed control of the induction motor dedicated to electric cars. The applied DTC speed control technique is a control method which offers a decoupled torque and flux control, it is the best alternative to the vector control, it is characterized by simple structure, fast torque dynamic and less sensitivity to the machine parameters. In order to confirm the effectiveness of this technique in controlling the speed of electric car motor, its algorithm was first implemented in the C block of the PSIM software platform, then it was implemented in DSP TMS320F28335 and both parts have been tested under New European Driving Cycle.

To simplify the understanding of the heart of this work, this thesis has been presented in three chapters. The first chapter has presented a state of the art on electric vehicles, starting with an overview about this type of vehicles, then revealed their evolution over time, their different types were named and classified according to their energy sources. Their traction chains structure and their different technologies were also given in the end of the chapter. The second chapter has presented a detailed explanation of the operating principle of the induction motor, then its mathematical model in the  $abc$  plane and then in the  $dq$  plane was demonstrated. At the end of the chapter, the induction motor model was simulated under an open-loop control in the PSIM software platform, where the obtained results were presented and discussed. Finally, in the third chapter, the most used techniques in the induction motor speed control were briefly presented, while a detailed explanation was given to the DTC technique through the presentation of its working principle, detailed mathematical equations and general structure diagrams. At the end of the chapter, the two parts simulation obtained results were given and discussed.

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- [19] 2 Loutfi Benyettou1 Salim Chakroune1 Abdelghani Aib1\* Djalal Eddine Khodja1. *FPGA Hardware in the Loop Validation of Torque and Flux Estimators for Direct Torque Control (DTC) of an Induction Motor (IM)*. Article, International Journal of Intelligent Engineering and Systems,A, 2021.
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العمل المقدم في هذه الرسالة هو مساهمة متواضعة لدراسة السيارات الكهربائية والتي تعد بديلا رائعا و انجازا قيما في تاريخ البشرية للسيارات الميكانيكية، والتي كانت بسبب الاحتراق الداخلي لمحركاتها سببا في تلوث البيئة، لكن هذا المشكل لا يوجد في السيارات الكهربائية التي استبدلت فيها محرك الاحتراق الداخلي بمحرك كهربائي حيث لا يوجد إفراز لثاني أكسيد الكربون الذي يعد أكبر ملوث للبيئة.

ينقسم هذا العمل إلى ثلاثة أجزاء ، الجزء الأول خصص للتعريف بالسيارات الكهربائية، أنواعها ومكوناتها وأنواع المحركات المستخدمة فيها ، بالإضافة إلى مزايا وعيوب هذا النوع من السيارات. في الجزء الثاني تحدثنا عن المحرك الغير متزامن والذي يعد الخيار الأفضل للاستخدام في السيارات الكهربائية. تم إجراء مقارنة بين نتائج المحاكاة والنتائج المرجعية والتي كانت متطابقة. في الجزء الثالث ، طبقنا تقنية التحكم المباشر في عزم الدوران من أجل التحكم الأمثل في سرعة دوران المحرك وبالتالي التحكم في سرعة السيارة ، بغض النظر عن حجم العزم المطبق. أظهرت نتائج المحاكاة كفاءة ودقة هذه التقنية في التحكم في سرعة محرك السيارة الكهربائية.

الكلمات المفتاحية: السيارة الكهربائية، البطارية، المحرك الغير متزامني ، نظام الجذب الكهربائي، التحكم غير المباشر في الحقل المغناطيسي ، التحكم المباشر في عزم الدوران.

## Résumé :

Le travail présenté dans cette thèse est une contribution à l'étude des voitures électriques, qui sont une merveilleuse alternative et une réalisation précieuse dans l'histoire humaine pour les voitures mécaniques, qui, en raison de la combustion interne de leurs moteurs, étaient une cause de pollution de l'environnement, mais ce problème ne se trouve pas dans les voitures électriques, qui ont remplacé le moteur à combustion interne par un moteur électrique car il n'y a pas d'excrétion de dioxyde de carbone, le plus grand polluant de l'environnement.

Ce travail est divisé en trois parties, la première partie était consacrée aux origines des voitures électriques, leurs types, leurs composants et les types de moteurs utilisés dans celles-ci, en plus des avantages et des inconvénients de ce type de voiture. Dans la deuxième partie, nous avons parlé du moteur à induction, qui est le meilleur choix par rapport aux autres moteurs pour les voitures électriques. Une comparaison a été faite entre les résultats de simulation et les résultats de référence, qui étaient identiques. Dans la troisième partie, nous avons appliqué la technique de contrôle direct du couple afin de contrôler de manière optimale la vitesse de rotation du moteur et qui permis de contrôler la vitesse de la voiture, quel que soit le couple appliqué. Les résultats de la simulation ont montré l'efficacité et la précision de cette technique dans le contrôle de la vitesse des moteurs de voitures électriques.

**Mots clés :** Voiture électrique, Batterie, Moteur à induction, Système d'attraction électrique, Contrôle orienté indirect du champ, Contrôle Direct du couple.

## Abstract :

The work presented in this dissertation is a contribution to the study of electric cars, which are a wonderful alternative and a valuable achievement in human history for mechanical cars, which due to the internal combustion of their engines were a cause of environmental pollution, but this is not found in electric cars, which have replaced the internal combustion engine with an electric motor as there is no excretion of carbon dioxide, the largest pollutant to the environment.

This work is divided into three parts, the first part was dedicated the origins of electric cars, their types, their components, and the types of engines used in them, in addition to the advantages and disadvantages of this type of car. In the second part, we talked about the induction motor, which is the best option than other motors for use in electric cars. A comparison was made between the simulation results and the reference results, which were identical. In the third part, we applied the direct torque control technique in order to optimally control the motor rotational speed and thus control the speed of the car, no matter how great the applied torque was. The simulation results showed the efficiency and accuracy of this technique in the electric car motor speed control.

**Keywords :** Electric car, Battery, Induction motor, Electric attraction system, Indirect Field Oriented Control, Direct Torque Control.