**MARMARA UNIVERSITY**

**INSTITUTE FOR GRADUATE STUDIES IN PURE AND APPLIED SCIENCES**

# BRUSHLESS DIRECT CURRENT MOTOR CONTROL METHODS AND APPLICATIONS

ALBAN EXAUCE MOUANDZA MBOUNGOU

**MASTER THESIS**

Department of Mechatronics Engineering

**Thesis Supervisor**

Prof. Dr. Mustafa Caner AKÜNER

ISTANBUL, 2019

MARMARA UNIVERSITY
INSTITUTE FOR GRADUATE STUDIES
IN PURE AND APPLIED SCIENCES

# BRUSHLESS DIRECT CURRENT MOTOR CONTROL METHODS AND APPLICATIONS

ALBAN EXAUCE MOUANDZA MBOUNGOU

o523516921

**MASTER THESIS**

Department of Mechatronics Engineering

**Thesis Supervisor**

Prof. Dr. Mustafa Caner AKÜNER

ISTANBUL, 2019

# MARMARA UNIVERSITY
# INSTITUTE FOR GRADUATE STUDIES
# IN PURE AND APPLIED SCIENCES

**Alban Exauce Mouandza Mboungou**, a Master of Science student of Marmara University Institute for Graduate Studies in Pure and Applied Sciences, defended his thesis entitled "**Brushless Direct Current motor control methods and Applications**",on 30/12/2019 and has been found to be satisfactory by the jury members.

**Jury Members**

Prof.Dr. Mustafa Caner AKÜNER (Advisor)
Marmara University

Assist.Prof.Dr. Ismail TEMİZ (Jury Member)
Marmara Üniversity

Assoc.Prof. Dr. Tahir ÇETİN AKINCI (Jury Member)
Istanbul Technical Üniversity

## APPROVAL

Marmara University Institute for Graduate Studies in Pure and Applied Sciences Executive Committee approves that Alban Exauce Mouandza Mboungou be granted the degree of Master of Science in Department of Mechatronics Engeneering on 05.02.2020 (Resolution no: 2020/05-02).

**Director of the Institute**
**Prof. Dr. Bülent EKİCİ**

# ÖNSÖZ

Elektrikli motorların kontrolü günümüzde endüstriyel işlem zincirinin en önemli alanlarından biridir. Pratik olarak, elektromekanik güç dönüşümünün tüm yönlerinde, elektrik motorlarının varlığı çok önemlidir.

Çalışmam, farklı tipte motorların sunumuna ve vektör genişlik modülasyonu tekniğinin uygulanmasına odaklanıyor. Bu teknik, simulink üzerinde uygulama ile programlamaya dayanmaktadır.

Bu araştırma, gerçek zamanlı kontrol sistemleri hesaplama hakkında daha fazla şey öğrenmeme izin veriyor. Bütün bunlar için aileme, özellikle de bu hatıranın yazılmasında beni destekleyen babam Albert ve annem Marcelline, arkadaşım Striciana'ya minnettarım.

Bu konuda çalışmama ve farklı teknikleri daha iyi anlamama yardımcı olan danışmanım Pr. Dr. Mustafa Caner Aküner'e teşekkür ederim.

**Eylül 2019** **Alban Exauce Mouandza Mboungou**

## TABLE OF CONTENTS

# LIST OF FIGURES

# LIST OF TABLES

# ÖZET

## FIRÇASIZ DOĞRU AKIM MOTORLARINDA KONTROL YÖNTEMLERI VE UYGULAMASI

Motor kontrolü, endüstriyel sistem mühendisliği alanındaki en ilginç çalışma konularından biridir. Günümüzde, endüstriyel bilişim, mekanik ve elektronik alanındaki enerjinin kullanımıyla ilgili zorluklarla birleştiğimiz gelişmelerle birlikte, yeni motor türlerinin geliştirilmesine ihtiyaç duyulmaktadır. Çok fazla enerji tüketmeden ve bakım maliyetini düşürmeden en iyi şekilde çalışabilme. Bu, fırçasız motorların nasıl geliştirildiğinden dolayı, arıza ve bakım riskini önemli ölçüde azaltan yoksundurlar. Daha sonra, bu tip motor oldukça yüksek motor torku geliştirir ve bu da asenkron motor için iyi bir alternatiftir. Bobin içindeki elektrik akımını değiştirmek için fırçalar ve mekanik anahtarlarla donatılmamış, bu eyleme izin vermek için yeni elektronik sistemler geliştirilmiştir. Bu sistemler sadece anahtarlamaya izin vermekle kalmaz, aynı zamanda motorun kendisini de kontrol eder. Bizim görevimiz, bu motorların farklı kontrol tiplerini sunmak ve hassas bir fırçasız motor durumu için bir hız kontrol sistemi gerçekleştirmektir. Fırçasız motorlar sensörler kullanılarak kontrol edilebilir. Kontrolü sensörsüz kullanacağız çünkü bu durumun olmaması, sensörlerin ve sensörlerin beslendiği elektrik kablolarının neden olacağı sorunların riskini azalttığı için daha avantajlıdır. Aynı zamanda motorun büyüklüğü üzerinde avantaj sağlayan etkileri olan motorun büyüklüğü azalır.

# ABSTRACT


## BRUSHLESS DIRECT CURRENT MOTOR CONTROL METHODS AND APPLICATIONS

Electrical Motor control is one of the most interesting subjects of study in the field of industrial systems motorering. Today, with the developments we are witnessing in the field of industrial computing, mechanics and electronics combined with the challenges associated with the use of energy, it becomes necessary to develop new types of motors that are able to operate optimally without consuming a lot of energy and reducing the cost of maintenance. This is how the brushless motors have been developed because they are devoid of which reduces the risk of breakdowns and maintenance in a considerable way. Then, this type of motor develops quite high motor torque, which makes it a good replacement for the asynchronous motor. Not equipped with brushes and mechanical switches to switch the electrical current inside the coils, new electronic systems have been developed to allow this action. These systems not only allow switching but also control the motor itself. Our job is to present the different types of control of these motors and to realize a speed control system for a precise case of brushless motors. Brushless motors can be controlled using sensors or not. We will use the control without sensors because it is more advantageous insofar as the absence reduces the risks of problems due to the sensors and the electric cables supplying the sensors. Also the size of the motor decreases which has advantageous effects on the size of the motor.

## YENİLİK BEYANI

Bu tez çalışmasının kendi çalışmam olduğunu, tezin planlanmasından yazımına kadar bütün aşamalarda etik dışı davranışımın olmadığını, bu tezdeki bütün bilgileri akademik ve etik kurallar içinde elde ettiğimi, bu tez çalışmasıyla elde edilmeyen bütün bilgi ve yorumlara kaynak gösterdiğimi ve bu kaynakları da kaynaklar listesine aldığımı, yine bu tezin çalışılması ve yazımı sırasında patent ve telif haklarını ihlal edici bir davranışımın olmadığı beyan ederim.

04/09/2019

Alban Exauce Mouandza Mboungou

# GENERAL INTRODUCTION

The electric machines hold a major place nowadays in the industrial domain. The realization of most of the industrial process requires the presence of the electric machines, whether to provide a mechanical energy necessary to the mechanical practices, or to provide an electric energy permitting to supply a chain of power.

Among these machines, starting from the machines using some strong intensities to those using weak currents, we do have the electric transformers, the electric converters of the electronic power regarding to the static machines, the motors and the electric generators along with the machines in motion.

More specifically, the use of the electric motors is inherent to the activity of the humans and the technical processes. In general, it is impossible today to provide a motor couple without using a motor, what makes of the use of the electric motor an obligatory choice. The complexity of the industrial tasks requires the use of motors also presenting very special features as the speed of rotation, the electric power capable to be provided in constant regime, the motor couple to the starting, the intensity of the acoustic noise and the controllability of the motor to mention these features only.

Among the electric motors, we find DC motors and AC motors. Each type of motor according to the nature of the energy used, presents very different functioning features and that can be sometimes very complex to the understanding, what has an influence on the techniques used concerning the control of these motors, whether for the control of speed, position or couple.

The control of the electric motors constitutes a concern still present for the companies and for the designers of rotary so-called electric machines. Indeed, the conception of the electric motors respects very precise constraints such as the adaptability, the controllability etc... All created machine must show a certain easiness to control, what will have for effect an efficiency in its requisite function. Today, the control of the electric machines becomes a fully-fledged domain of the science considering the importance behind the piloting of the motors to adapt their working to a notebook which very often is a technical constraint necessary to the motion of an industrial task.

The progress of the Power electronics with the development of the electronical conductors and the static converters as the choppers, rectifiers and inverters made possible the development of several motor control systems which in themselves constitute control techniques. Furthermore, these techniques still present some limits in the realization of their requisite functions [1]. Beside the progress of the electronics in general, it is fundamental not to forget the contribution of the software of simulations such as MATLAB/Simulink that permits in an environment without risk to conduct tests of simulations of any type of electromechanical system. With the contribution of the simulation software, the recent works developed in the domain of the control of the electric motors do not only limit themselves. To present the techniques of control that already exist, but they rather go deepening the theoretical and practical knowledge as well that we have on the working of the electric machines and they search for the means to develop new types of more efficient control while leaning on new concepts or on the limits and ways of research of works developed by our predecessors.

This thesis is a work about the control of motors with direct current without brushes and more specifically on a very particular technique of the control of these motors that is called control without sensors. Two techniques allow to control the motors to alternating current without brushes: the technique of control with sensors which uses some sensors as the sensors of position and speed, Hall effects sensors, the sensors to variable reluctance [1] and the technique of control without sensors that are based on other technologies to allow the control of the motor. This thesis aims to present all these techniques of control and to make a deepening on the technique of control without sensors while achieving a simulation.

Having been at first motors of secondary importance, today, considering the progress achieved notably in electronics with the design of transistors, electronic cards, microprocessors, the microcontrollers of various categories and the progress in theory of control. These motors represent a big way toward applications till now unexpected as in the conception of the drones [2] in the military domain, in the car, aviation and a lot of other applications. All it is due to the features of these motors that are for example the high speed, an absent acoustic noise, a high efficiency, a fast-dynamic response couple features satisfying.

Thus, to get an efficient functioning of the motor, it is necessary to understand it in depth to know how better to control it, what requires passing necessarily by the stages of simulation that permit to collect convenient data and to compare them to the theoretical data.

# CHAPTER 1: PRESENTATION OF ELECTRIC MOTORS

An motor, in general, is a device capable of transforming any form of energy into mechanical energy that will be used to produce a mechanical torque and which will most often aim to generate a circular or linear motion. Thus, an electric motor is a machine whose role is to convert electrical energy into mechanical energy. The electrical energy in this kind of system constitutes the primary energy or power supply of the motor. Mechanical energy in turn constitutes secondary energy or output energy, which allows any system to perform its required function.

In summary, an electric motor is therefore a converter of electrical energy into mechanical movement. The energy used by electric motors can be presented under two very well-known aspects: the alternative nature that generates a system of voltage and alternating current and the continuous nature that generates a system of continuous voltage and current. There are several types of electric motors and each of them uses one or the other of these two kinds of electrical energy for their power supply. Motors using alternating current are called AC motors and those using continuous one is the family of DC motors.

## 1.1 Voltage and Current Systems

There are two major forms of electrical energy: Alternative energy and continuous energy. The electrical energy is featured by two electrical quantities which are the voltage and the electric current.

By definition, the electrical voltage characterizes the potential difference between any two points and it is the necessary pressure that must be applied to the electric charge carriers to set them in motion. This movement which can be characterized by a flow of electrons through a conductor portion is the electric current.

The voltage is characterized by the symbol $U$ or $V$ and the current is characterized by the symbol $I$. Depending on whether one is in AC or DC mode, the representation of voltages and currents can become a little more specific taking into account the characteristics of the different current regimes.

## 1.2 The Alternatives Magnitudes

Among the alternative electrical magnitudes, we find the AC voltage and the AC current which are, with the frequency, the two most important magnitudes allowing to characterize an alternating electric network.

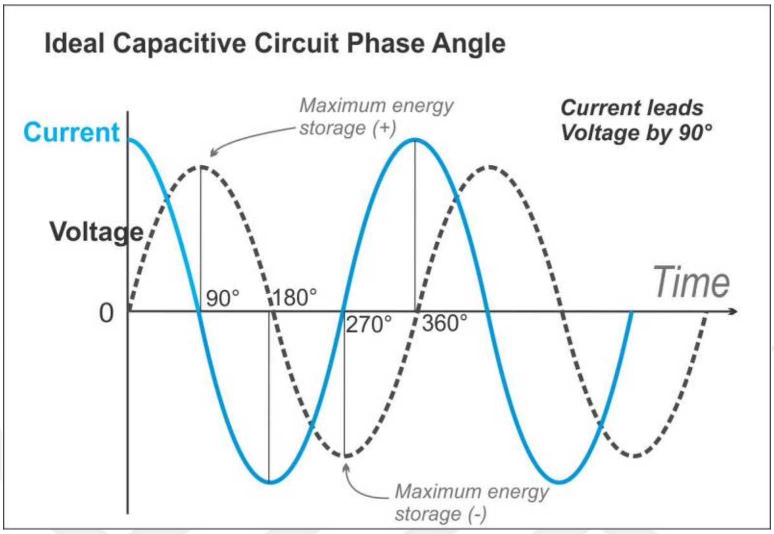



**Figure 1.1** Representation of alternative magnitudes.

### 1.2.1 The alternative tension

AC voltage is the voltage naturally produced by electrical voltage generation systems that are usually power station. To generate an alternating voltage, the presence of an alternator is necessary. The AC voltage is an instantaneous voltage, that is to say that its value varies over time as Figure 1.1 shows a representation of the AC voltage.

**a.The Alternator**

The role of an alternator is to transform mechanical energy into electrical energy. As a whole, an alternator is made up of an armature circuit and an excitation winding. The armature circuit is constituted of three coils distributed on the stator spaced from each other by 120º. The excitation winding is in turn a winding wound on the rotor and traversed by the DC excitation current. It allows the creation of magnetic poles called rotors and the introduction of a given flux in the magnetic circuit. In an alternator, the armature is on the stator and the inductor is on the rotor. An alternator operates on the principle of the induced voltage, the excitation circuit on the rotor is supplied by a DC voltage and therefore produces a fixed magnetic field. When the rotor is driven by an external device, the constant magnetic field from the excitation circuit is seen as a magnetic field when it periodically scans the coils spaced 120º apart on the stator.

These coils being traversed by a variable magnetic field induce sinusoidal electromotive forces as shown in Figure 1.1, therefore variable in time and space, which in turn produce an alternating voltage across the electric machine. This is how alternative energy is produced in a conventional way.

### 1.2.2 The Alternating Current

After the alternator has produced AC voltages, and these voltages are present at these terminals, the connection of a load that is of resistive, capacitive or inductive type will cause the alternator to charge a current of some intensity in the load. Let us remember that the loads do not consume voltages but rather alternating currents under a certain voltage. The current absorbed by the load will be characterized by its intensity that is to say its value and by its frequency which represents the number of round-trip performed by the latter between the load and the system of production of the alternating voltage. The shape of the electric current is almost often similar to that of the voltage. In resistive circuits, this is strictly the case because the voltage is proportional to the current by the resistance factor.

## 1.3 The Continuous Quantities

The Continuous quantities include DC voltage and DC current. Different quantities representing alternative systems, voltage and direct current have no frequency. The peculiarity of these quantities is that they have no instantaneous value as for the voltage and the alternating current. Their numerical values and waveforms do not vary over time whether for a resistive, capacitive or inductive circuit. Furthermore, the circuits supplied under this regime do not provide much information transiently because the continuity of the electric current nullify the derivatives of these circuits. The Figure 1.2 shows a representation of the continuous quantities in a graph with a comparison to the alternative quantities. It is easy to make the difference and to notice the difference of the waveforms of the different electrical quantities.

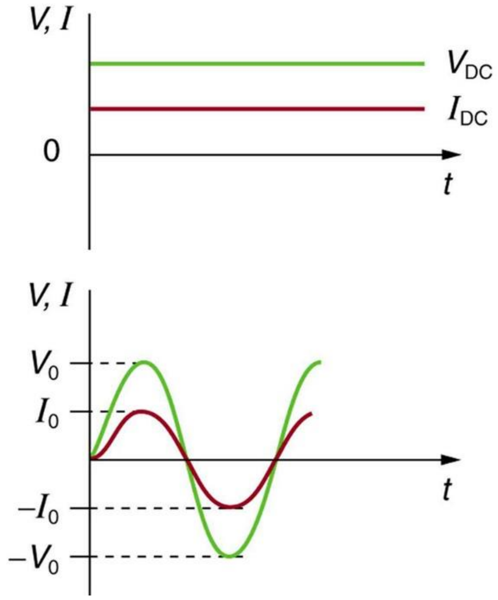



**Figure 1.2** Representation of continuous electrical quantities.

### 1.3.1 The Continuous tension

The DC voltage, in turn is produced by electric generators called dynamo. By using a magnet, we have the presence of a constant magnetic field and when a coil is placed in the magnetic field and it is set in rotational motion, there is an electromagnetic induction phenomenon which causes a variation of the magnetic flux and the creation of an alternating induced electromotive force which after the collector of the machine becomes a continuous form electromotive force.

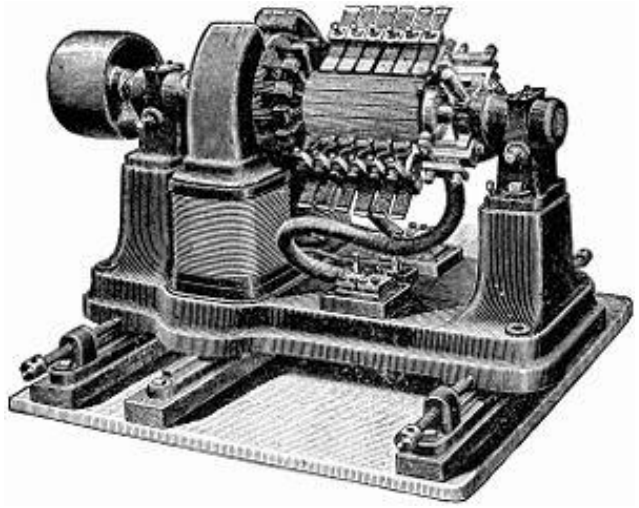


**Figure 1.3** Electric Dynamo

Nowadays, the use of dynamos is over in industrial processes. All applications requiring large-scale continuous currents and voltages firstly involve the production of alternative electrical energy systems. Thanks to the progress made in power electronics with electronic switches, it is possible by using systems called rectifier to obtain a continuous energy from an alternative energy.

### 1.3.2 The continuous current

The electric charges connected to the electric generators do not consume voltage but rather electric current, the nature of the electric current is thus determined by the nature of the electric voltage produced by the electric generator. If the voltage is alternative, the current will be too. If the voltage is continuous, the current will also be of a continuous nature.

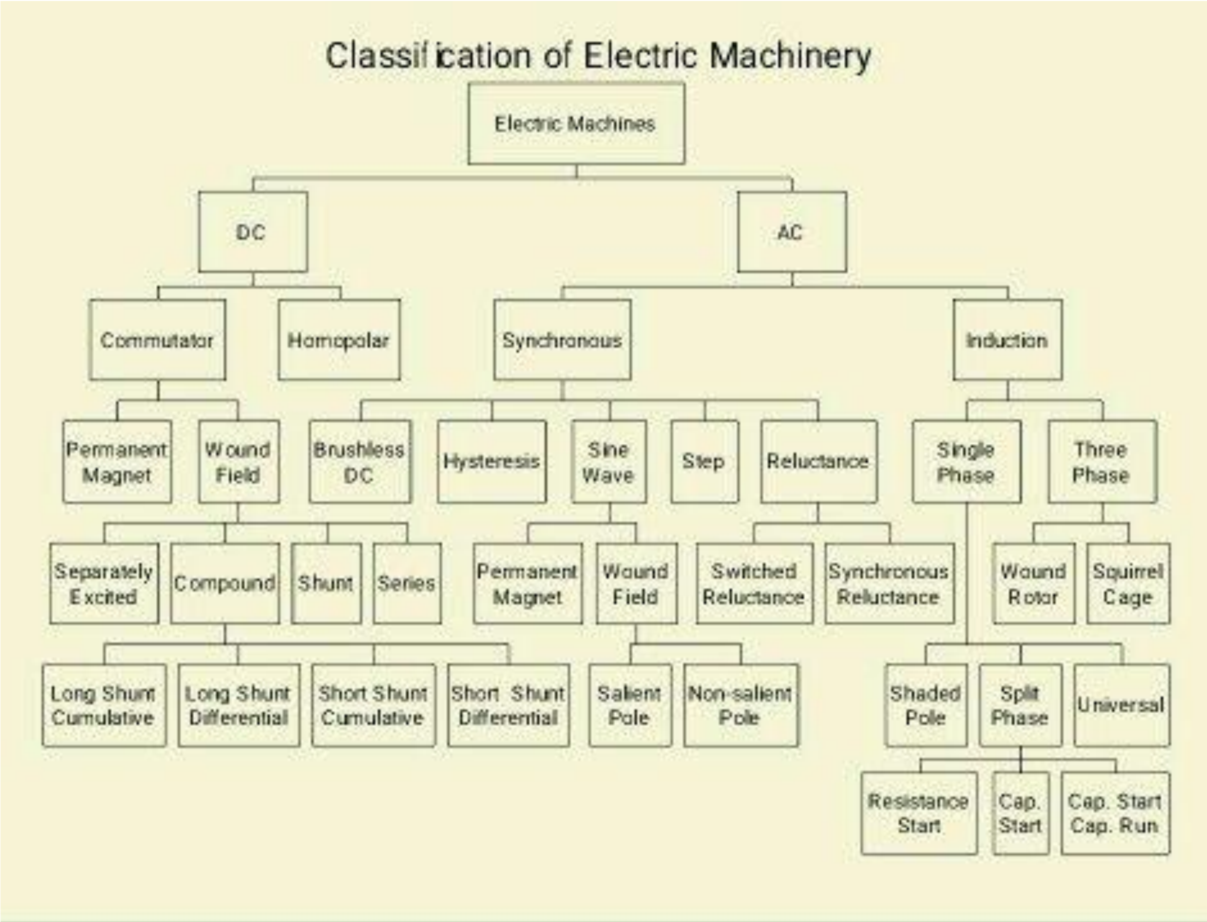
## 1.4 Classification of Electric Motors

Electric motors are divided into two major groups: AC motors and DC motors. Table 1.1 supplies a much more detailed view of the classification of rotating electrical machines, that is to say the one whose function is to transform mechanical energy into electrical energy or vice versa.

AC motors include asynchronous motors, AC brush motors, universal motors and synchronous motors. The family of DC motors is in turn made up of universal motors, brushless motors commonly called brushless motors, compound excitation motors, shunt excitation motors and series excitation motors.

One of the most important things to retain in this classification of electric motors is that no electric motor exists in the natural state. All electric motors are of industrial manufacture. This means that electric motors are developed to solve an motorering problem, in other words, each electric motor has some characteristics that are unique to it, which justifies its design.

**Table 1.** Classification of Electrical Machinery




### 1.5 The DC Motors

#### 1.5.1 Shunt excitation machines, separate and permanent magnet

Shunt excited excitation machines and permanent magnet machines, although having a different electrical structure, have almost the same function when powered by a constant voltage source. However, the shunt excitation machines have a slight difference because the excitation voltage is different.

The previous machines presented from their electrical structure perspective, an excitation circuit connected in parallel with the armature circuit of the motor. This is different for the series excitation motor which has its excitation circuit connected in series with the armature circuit, which means that the excitation current has the same value as the power supply current of the electric motor. This motor has the advantage that, the inversion of the polarity does not cause a reversal of the direction of rotation of the rotor. Apart from this electrical advantage, from the mechanical perspective, this type of motor allows to develop some very high torque even at low speed. It is most often used for traction applications.

The inconvenient with the series motor is that it must never start empty or it will run, it must be loaded enough to be turned on.

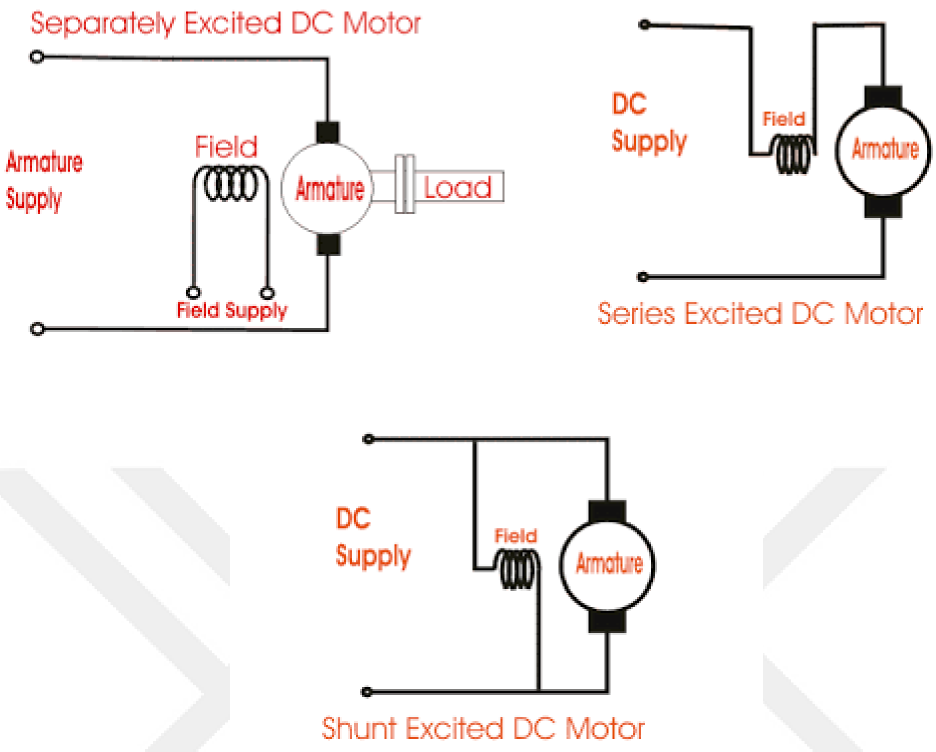



**Figure 1.4** Representation of shunt excitation machines, series and separate.

### 1.5.2 The Compound excitation machine

The compound excitation machine is a machine which combines the characteristics of a shunt excitation machine and a series excitation machine.

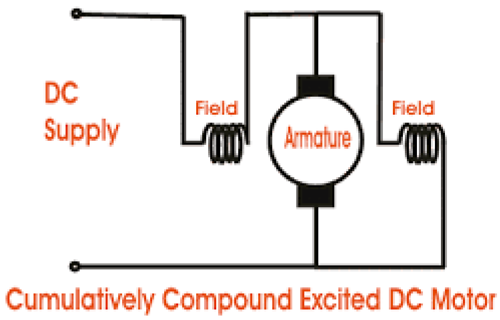



**Figure 1.5** Compound excitation machine

The shunt characteristic is considered when the machine is not running under load and the series characteristic is completed when the motor is running under load. This kind of connection allows us to obtain an undercurrent machine with series excitation but having the possibility to operate without load thanks to the shunt connection which allows to fulfil additional function compared to a pure machine with serial excitation or a pure machine shunt excitation.

### 1.5.3 The universal machine

The universal machine is a DC machine by its design but has the advantage of operating either by being supplied with direct current or by being supplied by alternating current. The basic equations of the DC machine are still applicable even in the case of AC voltage operation as the nature of the voltage source. The universal motor behaves much like the serial motor which can also be powered by an AC voltage.

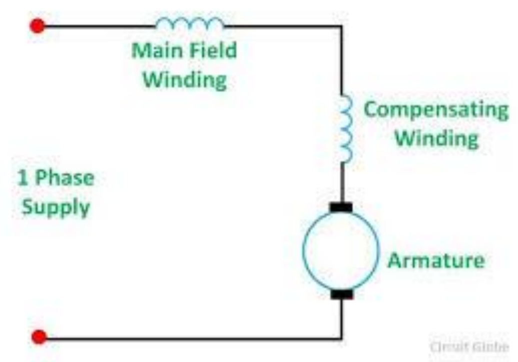



**Figure 1.6** The Universal Machine

These types of series motors, which are used as a universal motor, have their applications in household appliances and machine tools, which require, at a frequency of 50 Hz, electrical powers not exceeding 1 KW, rotational speeds not reaching 700 rpm and can be with the variation of the supply voltage.

## 1.6 Alternate Current Motors

### 1.6.1 Induction machines

Induction machines are electrical machines that operate on the principle of electromagnetic induction invented by Faraday. This law states that as soon as there is a magnetic field in a coil or turn, this magnetic field induces an electromotive force called induced electromotive force. If the circuit is closed, there will be a current in this circuit. The asynchronous motor, usually an induction motor, is a motor in which the expected current in the rotor to produce the torque is produced by the electromagnetic force induced on the rotor by the magnetic field generated by the stator coil.

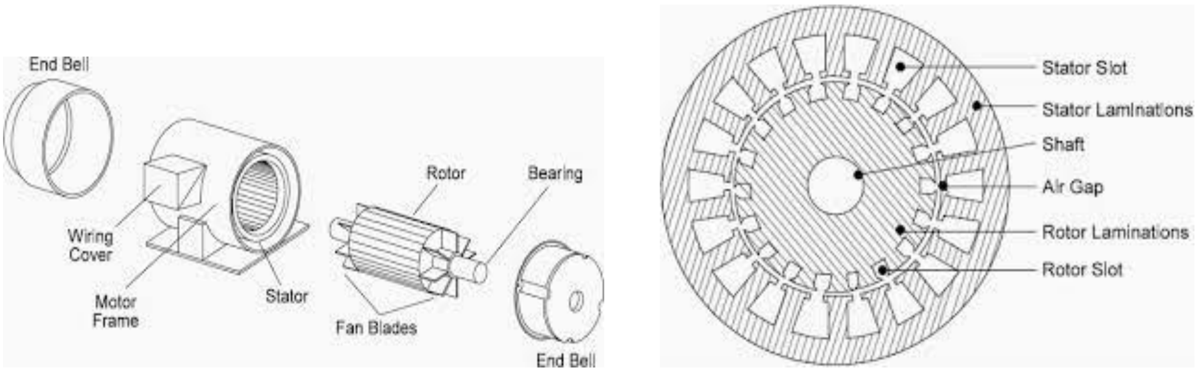



**Figure 1.7** Representation of the induction machine

Unlike DC motors, the asynchronous motor does not have a switching system because there is no electromechanical connection between the stator and the rotor. The result of such a system is that the problems of motor wear or crash due to the deterioration of the brushes is eliminated. Among the advantages, it can be noted that:

• The asynchronous motor can be robust and have very high power levels.
• It also requires little maintenance.

Regarding its disadvantages,

• There is a strong dependence between the load and the speed developed by the motor.
• A peak of current at ignition.

Synchronous machines are also another set of AC machine used in industry in very specific applications. Contrary to asynchronous machines, synchronous machines have an operating principle like asynchronous machines.

### 1.6.2 Synchronous machines

Synchronous machines are most often seen as alternators because they are widely used in the production of electrical energy. Alternators are electrical machines that convert mechanical energy into electrical energy. The property of these machines is that the rotor frequency is the same as the frequency of the rotating field, so that in motor operation, the speed of rotation is always equal to the synchronous speed. Thus, synchronous machine served for a long time to privileged applications while the asynchronous machine was the industrial machine. Later, with the developments of power electronics, we have a new perspective.

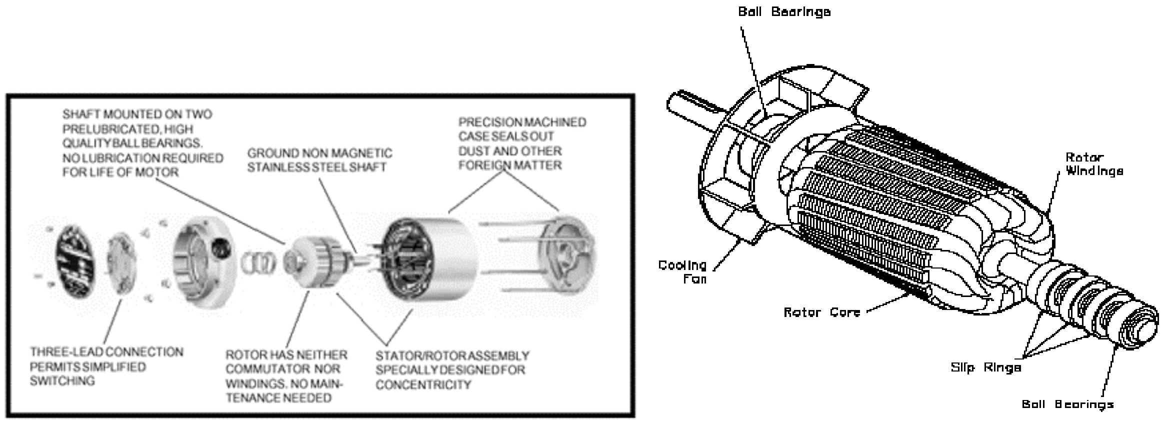



**Figure 1.8** The Synchronous Machine

Progress in semiconductor (power) technology have made it possible to power synchronous motors by enabling them to behave like switching machines without presenting mechanical challenges (which is the autopilot method). Besides that, the manufacture of a new type of permanent magnet made it possible to switch to synchronous machines with permanent magnet. The advantage of using the permanent magnets to excite the S.M has improved the operation of the S.M qualitatively but also to give the machine some properties related to the configuration of permanent magnets in the exciter circuit. These properties could now be aligned with the applications for which the machine was designed. Such developments have made it possible to make progress in the power range in which the SM could now operate and where low power applications were going to very powerful applications such as rail traction for example (Michel LAYOUE-MAZENE, Director of research emeritus at the CNRS LEEI-ENSEEIHT / INPT).

The operating principle of the synchronous machine has been elucidated above but in summary, we can say that the synchronous machine operates on the Faraday principle which shows that if the magnetic flux in a loop varies with time, a voltage is induced. This is valid for generator operation. The principle of Laplace is used for motor operation, this principle states that when an electrical conductor is placed in a magnetic field and is traversed by an electric current, then a force is exerted on the capacitor. When this principle is applied to a set of coils distributed in a circular manner and spaced by an angle of 120 °, then there is creation of a circular motion, which is characteristic of the typical movement of an electric motor rotor. Synchronous machines like all machines have advantages and disadvantages. Regarding their disadvantages:

• Maintenance of brushes for medium and large motors

• A possibility of stall when the requested couple is too high

• Need an additional device to allow start up on the network.
And as advantages:

• To create the same expectations as an asynchronous motor thanks to semiconductor technology and the development of higher performance permanent with efficiency.
• To have a fixed speed whatever the load.

The high cost of synchronous machines means that they are not generally used as motors. They are more used as alternators to produce electrical energy, in applications requiring a stable speed depending on the load, and as special motors like brushless, stepper motors.

### 1.6.3 The universal motor

The universal motor as its name suggests is a type of electric motor that can operate by receiving an alternative power supply as well as receiving a continuous power supply. The use of an additional device to make these two types of power supply possible is not necessary. This characteristic of the universal motor is due to its electrical design at the level of its armature and its inductor. The design of the universal motor is based on that of the series excitation motor. The goal in this electric motor being developed a motor torque, the direction of rotation of a universal motor does not change even when (the polarity) of the current changes, which is a great advantage in an AC voltage operation. In DC mode, it is necessary to reverse the polarity of the armature or inductor which requires an additional device. Just like the series motor, the universal motor is racing empty. The frequency of the current has no effect on the speed of rotation. This rotational speed decreases as the load increases. A phi cosine and a bad performance. A good start couple.

### 1.6.4 Variable reluctance machines

These machines also called Vernier machines are electromagnetic devices whose operating principle is based on the minimization of reluctance. The reluctance is the equivalent of the electrical resistance, the reluctance characterizes the ability of the magnetic circuit to oppose the passage of the magnetic flux in the circuit. This principle, also called the electromagnet, is the oldest method of converting electrical energy into mechanical energy.

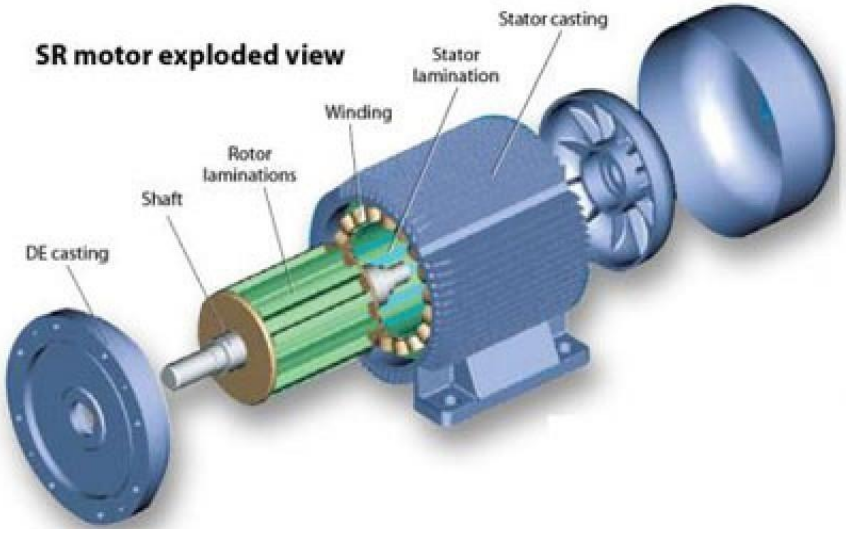



**Figure 1.9** Variable Reluctance Machine

They consist of a stator and a rotor in relative motion. One of the parts being electrically active and the other passive. Reluctance machines do not operate independently as DC motors which are provided with collector brushes system whose role is to ensure the communication of the current in the armature circuit which continuously permits the rotation of the rotor. Variable reluctance machines also use transducers such as encoders to detect the rotor position, because in a variable-reluctance motor, to ensure the rotation, it is necessary to magnetize the stator in certain specific places. The phases of the stator being all the same, it is necessary to know which of the phases will be excited to minimize the reluctance and to allow the rotation of the rotor. Reluctance machines in general have a great simplicity of construction and a possibility of reducing the cost of manufacture, which also affects positively the purchase price of the machine. Nowadays, there are two main types of variable reluctance machines: synchronous reluctance machines and double-sided variable reluctance machines (Synchronous Reluctance Machines) and (Switched Reluctance Machines). The first type is that of rotating field machines in which the excitation circuit is only on the stator. The second type is pulsed field machines. In this type of machine, the stator contains electromagnets that attract the poles of the rotor and they are supplied only with unidirectional current, which is not the case of the first type which is rather supplied with sinusoidal alternating current.

The advantage of this machine is first economic because the cost of materials and the manufacturing cost are relatively affordable. Then, from a technical prospective, the machine can operate in very external conditions whatever the temperature, having neither magnets nor collector. Finally it has a robustness and an appreciable operating safety.

With the progress made in improving the operation of these machines, whether those with rotating field or pulsed field, the possible applications of these machines are first the household appliances, the washing machines are a convincing example, in traction of electric vehicles, and further applications in space and aeronautics.

### 1.6.5 Linear machines

To meet industrial applications, instead of using rotary motors, one rather use linear motors. From the point of view of differences, there are no great differences between a linear motor and a rotary motor except for their geometric configuration in space and in their operation. A linear motor is an electric motor that has been unrolled and that now produces a linear force along the length by installing an electromagnetic field displacement. It consists of a movable part, the slider, comprising the magnets and a fixed part, the stator comprising the coil, the position sensors, the thermal protectors.

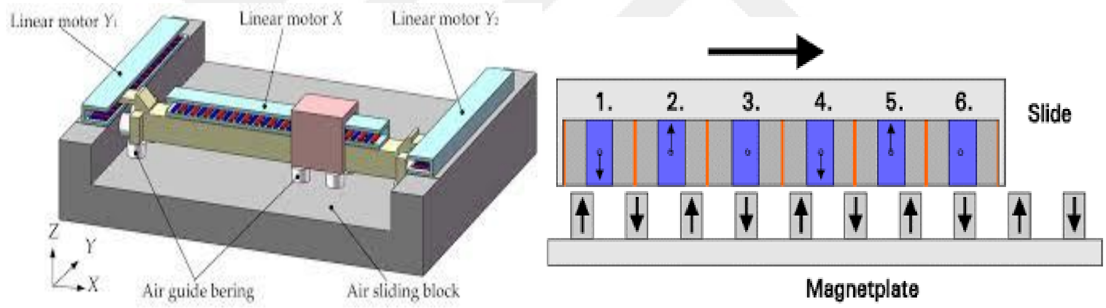



**Figure 1.10** Linear Motor

The operating principle of a linear motor is not different from that of a rotary motor. In this principle of operation, we always find the same elements but with a different layout, this is the case of coils and magnets. It aims to produce a force because the movement is linear and not rotational. The linear displacement is under the effect of the electromagnetic force under no other assistance.

The advantage of this type of motor is found in a simplification of hardware. The use of a rotary motor coupled with other ancillary systems to produce linear motion is no longer necessary. The disadvantage of linear machines is a very poor dissipation of heat produced by Joule effect. Linear motors have a long life, synchronized movements, and a high dynamic. Its cost of use is reduced, easy integration, a wide range force / speed.

Linear tubular motors are an excellent solution for replacing pneumatic cylinders. They are also used in demanding industrial applications.

### 1.6.6 Hysteresis machines

As its name suggests, the hysteresis motor is an electromechanical energy converter that uses the hysteresis phenomenon to generate torque at the rotor. This type of motor is not new but has never known a large expansion. Not to mention that the magnetic hysteresis depends on the material used, the cause of non-expansion of hysteresis motors is related to this. The efficient operating characteristics of a hysteresis motor largely depend on the materials used.[5]

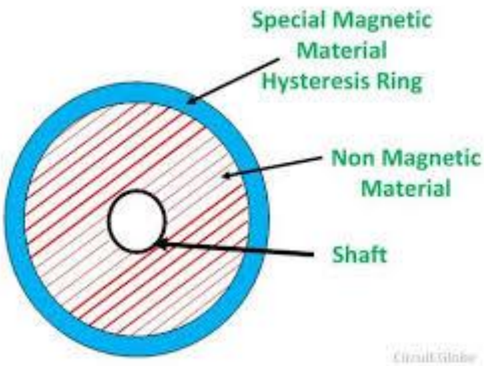



**Figure 1.11** Hardware Requirement of the Hysteresis Motor

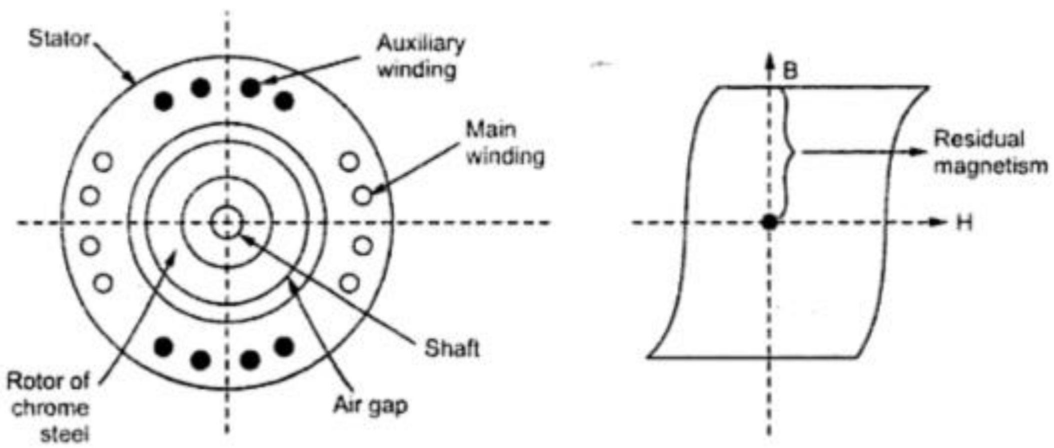



**Figure 1.12** View of the hysteresis motor and stator hysteresis.

Like any electric motor, the hysteresis motor consists of a stator and a rotor. The stator is designed in salience and when excited, produces a rotating magnetic field. The rotor is constituted integrally of a ferromagnetic material. The resulting torque will result from the interaction between the flux induced in the rotor and the magneto motive force. The hysteresis motors have a smooth and quiet operation, and this due to the smooth surface of the rotor, a constant torque, a moderate current at startup. The characteristic of the hysteresis motor is that the rotor is very solid and consists of a material having a high degree of magnetic hysteresis. The rotor is most often cylindrical. The most commonly wound stator receives alternating currents necessary to produce the couple.

The disadvantage of the hysteresis motor is low efficiency, low developed power, oscillation phenomena. There are two main types of hysteresis motors: cylindrical hysteresis motors that have a cylindrical rotor, and either composed of a hysteretic material or a mixture with a core formed of a non-hysteresis material.

Disk-shaped hysteresis motors. The space between the rotor and the stator is between the flat side of the disk and the stator.[6]

### 1.6.7 Piezoelectric Motors

The piezoelectric term conveys much more than the group of words into which it can be inserted. Briefly, piezoelectric comes from piezoelectricity. Piezoelectricity is the property of some bodies to be electrically polarized under the action of mechanical stress (reverse effect). From this term, the piezoelectric effect has paved the way for another type of motor called piezoelectric motors or piezomotors. Like all motors, they consist of a fixed part and a moving part. The alternative deformation of a fixed structure using certain types of so-called active materials, causes a uniform mechanical movement to a moving part. During this transfer of energy, it is by means of friction that the drive movement of the fixed part is generated.

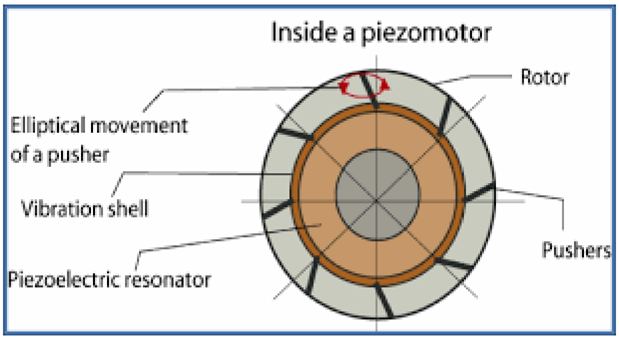



**Figure 1.13** Representation of a Piezomotor

In the piezomotors family, there are three main categories of motors:

• **Inchworn motors** that use a principle close to the movement of an earthworm with a succession of elongations / contractions interspersed with phases of hooking forward or backward.

• **Ultrasonic motors,** which use piezoelectric materials to generate elliptical contact between the rotor and the stator.

• **Inertial motors** that rely on alternations between slow and fast movements. [Christian Belly, Inertial piezoelectric motors: designs, achievements, test-tests, December 08, 2011, France]

The advantages of piezomotors are numerous:

• Potentially high power density compared to a motor DC.

• Low noise level

• Simple manufacturing

• No electromagnetic disturbances

•High torque

Disadvantages:

• Need for high frequency power source

• High cost

• Complex power supply

Applications

Watches, micro robotics, automobile, Mems

### 1.6.8 Stepper motors

The steppers like any electric motor, electromechanical converters. Stepper motors are also part of a class of electric motors that are called special motors in relation to their configuration or their way of absorbing electric current from the power source. Stepper motors convert electrical energy, in the form of an electrical pulse signal, into mechanical movement.[7]

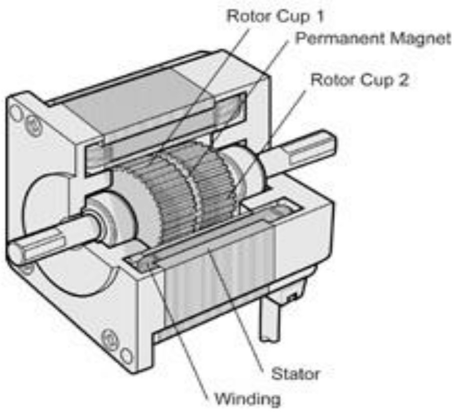



**Figure 1.14** Stepper motor

In its mechanical constitution, the stepper motor has a constitution close to the synchronous machine. Its stator carries the windings, its rotor is provided with permanent magnets in the case of so-called polarized or active structures. In the case of reluctance or passive structures, the rotor consists of toothed ferromagnetic part. Both stator and rotor have salient poles. Conventional power supplies are either AC or DC. These are power supplies whose flow of electricity is constant like a stream of water flowing in a river. The stepper motor does not receive power from such sources because it is powered by electrical impulses. To do this, between the motor and the power source, elements are added to meet this requirement. There is thus: a unit which generates the control pulses of the electronic switching contactors, a power electronics system for switching, responsible for supplying the energy to the windings of the motor at precise moments.

The principle of operation of the stepper motors is based on the switching of the windings of the stator, the stator on which the phases are mounted. The electronic pulse is translated by a sequencer. The sequencer in turn controls the electronic switches which according to their opening times will distribute the polarities in the stator windings. Each switching generating just one step, a continuous switching is necessary to generate several steps to create a rotational movement equivalent to a complete revolution of the rotor. All configurations of the voltages across the windings correspond to a displacement of the stable position of the rotor.

### 1.6.9 Brushless Motors

Brushless motors as under the abbreviation of BLDC Motors Brushless Direct Current Motors that can be translated into French DC motors without brushes, come to solve the problems related to energy consumption. For example, in the automotive industry where permanent magnet and high-performance motors are required as necessary characteristics to allow optimal operation of hybrid vehicles.

Compared to DC motors, from a structural perspective, the bldc motor looks exactly like the DC motor. The only notorious difference lies in the system allowing the switching and the transfer of electric current. DC motors are equipped with brushes and a mechanical switch. The bldc Motors, on the other hand, take great advantage in eliminating this mechanical system which is subject to repetitive breakdowns and replace it with an electronic system whose purpose is to ensure the same switching function. [10]

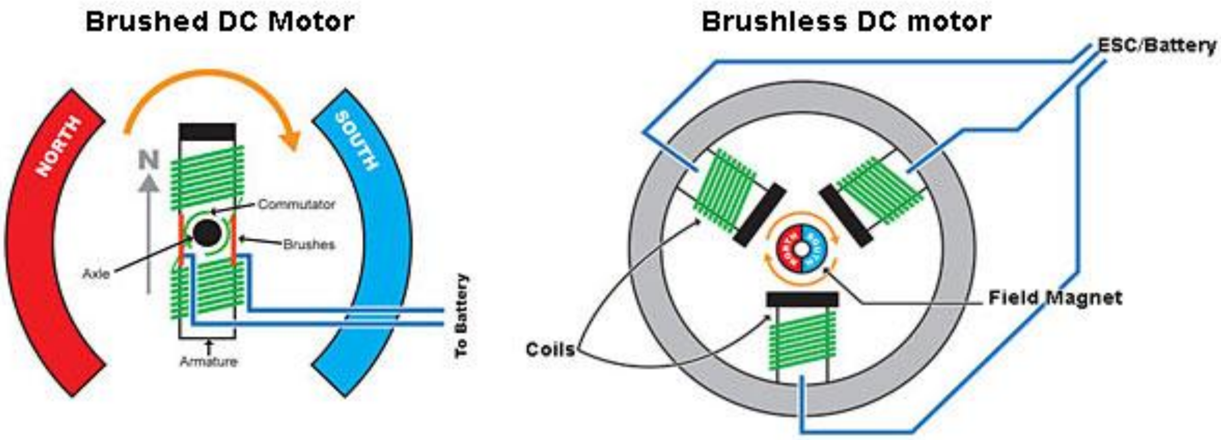



**Figure 1.15** Brushless Motors (right) and DC Motors (left)

The interest of the BLDC motors is great, not only like the DC motor, it has a linear characteristic between the torque and the current, between the speed and the electric tension at the terminals of the motor, which makes it very easy to the control of speed and torque, it also has a high dynamic response, it is efficient and safe, it operates without noise, it has a long life, it can reach very high speeds, a reduction of electromagnetic interference. In addition to this, it can operate in very external conditions where the use of a DC motor or an induction motor would have structural, qualitative and quantitative limits.

We must call motors without brushes, all electric motors that operate without physical electrical connection between the stator and the rotor.

These motors are also defined as permanent magnet motors. There are two main types of synchronous motors without brushes: Synchronous motors with permanent magnets, Magnet AC synchronous motors and motors without dc, in English BLDC motors for Brushless Direct Current Motors.

## 1.7 Conclusion

At the end of this first part, we can tell that we design by electric motors all motor which is able to convert any electrical energy into mechanical energy. For how study, the motor converts the electrical energy into a torque. The motion is circular and when the motor rotate its produces any torque in order to make another system moving. In this kind of work. There are many sort of electrical motors and each of them work with distinct characteristics.

# CHAPTER 2: PRESENTATION OF BRUSHLESS MOTORS

## 2.1 Introduction

Brushless motors, as their name suggests in opposition to brush motors or ballast motors are a type of electric motors without brushes or coals. DC motors in general are provided with a system called brush-collector whose purpose is to provide electrical switching in the armature circuit to allow rotation of the motor. The consequence and the disadvantage of this type of electric motors are the rapid wear of the brushes, which requires periodic maintenance necessary for the proper functioning of the machine.

A BLDC motor is a set of permanent magnets rotating in front of a set of electrical conductors of continuous current during a rotation angle most often set at 60 degrees. Figure 2.1 is a representation of an motor of a DC motor and a BLDC motor. The structural difference of the two machines is easily visible. The absence of brushes on the BLDC motor requires the use of a system to remedy it.[10]

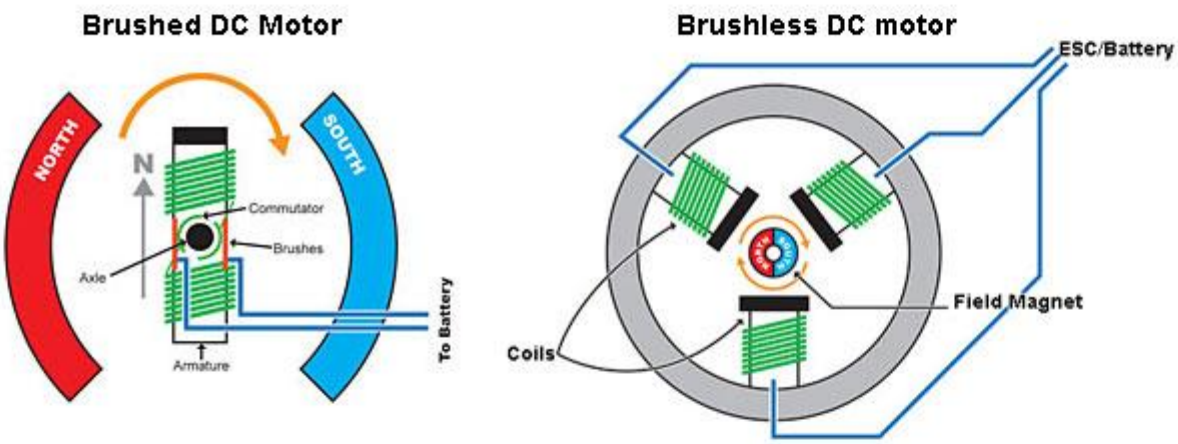



**Figure 2.1** From left to right, representation of a DC motor and a BLDC motor.

The current inside the electrical conductor must change polarity whenever the magnetic poles pass. The role of switching ensures that the polarity change is made in such a way that the torque remains unidirectional. Therefore, in a certain sense the change of polarity is called switching.

Conceptually, a BLDC motor is not so different from a conventional DC motor. The significant difference lies in the switching system used on both machines.

## 2.2 Definition of a Brushless Motor

A brushless motor is an electric motor that has no brush, no commutator and a lack of the mechanical switching system as in conventional DC motors. From this name, we could list a range of electric motors with this characteristic such as shared reluctance motors for example. The particularity of the brushless motor is that in addition to bringing together these different characteristics, the machine is a synchronous type machine [2]. This is to say that the speed of the machine is the same as the speed of the rotating field. The speed is therefore related to the frequency of the network and the number of poles of the machine as is the case of synchronous machines.

$$N = \frac{f \times 60}{P}$$

*f is the frequency of the network P the number of pole pair of the machine N the speed of the machine which is also the speed of synchronism*

We can define a motor by its name, but this is not completely true for brushless motors even if they are types of motor without brushes. Under this name of brushless motor, there is a whole range of electric motor with principles of operation very different from each other. We can still agree that the function of the brush-collector system exists in another form in these types of motor and that on this point, the operating principle of this system remains almost unchanged scientifically.

Depending on the mode of operation, whether under a system of continuous voltages or a system of alternating voltages, the brushless motors have very specific names. When operating under a set of electric square waveform currents, they are called Brushless Direct Current Motors (BLDC) and when they operate under a system of AC voltages, they are Permanent Magnet Synchronous Motors (PMSM). They are all three-phase motors but the characteristics of the signals that supply them are very different.[1]

### 2.2.1 Presentation of permanent magnet synchronous motors.

As the name implies, permanent magnet synchronous machines are the sort of machines whose magnetic structure is characterized by permanent elements as shown in Figure 2.2. Such a machine therefore requires permanent magnets of high quality so that its operation is optimal and meets the requirements. Synchronous machines with permanent magnet, in recent years have really developed, making themselves appreciable on the market, thanks to the development of permanent magnets of high quality.

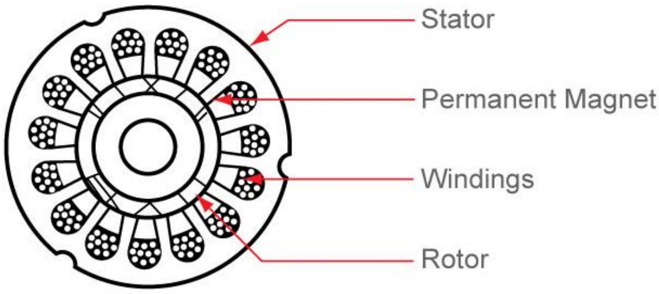



**Figure 2.2** Permanent Magnet Synchronous Motor Diagram

Synchronous machines with permanent magnets can be very different from the point of view of the disposition of the permanent magnets inside. Therefore, although having the same name, the difference is seen in the benefits provided by the various provisions and applications that result. In synchronous machines with permanent magnets the arrangement of the magnets is made so that the flow distribution inside the machine is sinusoidal.

### 2.2.2 Structure of permanent magnet synchronous motors.

The structures most used in the design of synchronous machines are the radial structures, which are ideal for surface mounting of the rotor. In this case, the air gap is uniform. As mentioned above, advances in the design of sufficiently powerful permanent magnets have made it possible to create electrical machines in which the excitation fields are produced by permanent magnets and electromagnetic poles as shown in Figure 2.2. requiring electric currents for their windings.

All this progress with advanced power transistor control has resulted in the replacement of mechanical switches with electronic switches and the creation of electronically commutated permanent magnet machines and intelligent control systems.[13]

Depending on the flux direction, radial flow machines and axial field machines are obtained. Since applications requiring high power densities are not common in everyday applications, radial field machines are more common than those with axial fields.

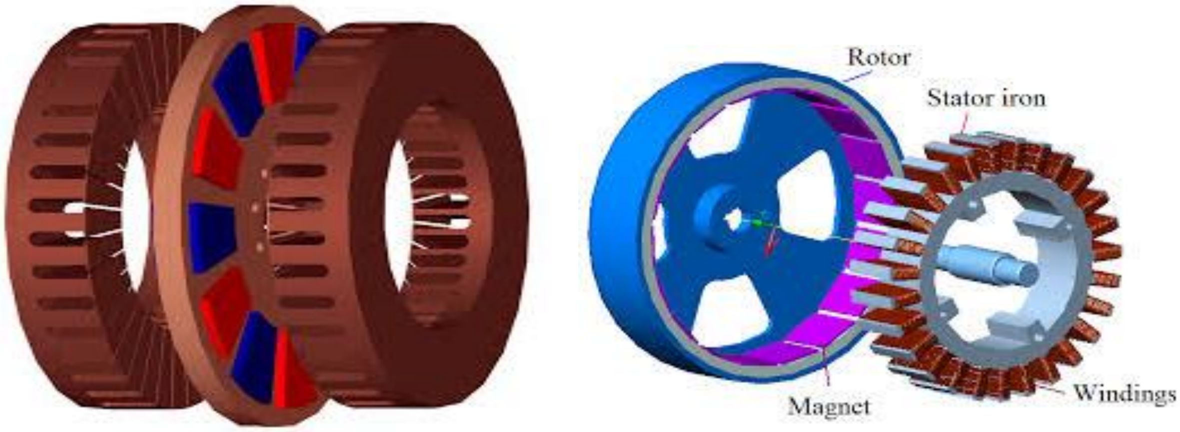



**Figure 2.3** Representation of a motor with axial flow (left) and radial flow (right)

Without going into details, it is necessary to remember that one of the most important elements in synchronous machines with permanent magnets is the permanent magnet. The provision of permanent magnets in the machine without changing the basic operation of the machine still has an influence on the geometric structure of the latter and generates several types of synchronous machines with permanent magnets. Among these types of machines, the following may be mentioned in order of frequency of use:

•Those whose magnets are mounted on the surface of the outer periphery of the rotor laminations.

•Those whose magnets are positioned in the grooves of the outer periphery of the rotor laminations.

•Those whose magnets are placed in the middle of the rotor laminations and oriented in the radial directions and along the circumference of the rotor.

•There is another type of permanent magnet synchronous motors whose role is to operate at constant speed and whose purpose is to improve efficiency and power factor, this type of motor has a cage structure of squirrel used to attenuate the oscillations of the rotor and to provide the couple.

### 2.2.3 Principle of operation of permanent magnet synchronous motors

The power supply system for permanent magnet synchronous motors is a three-phase voltage system. The permanent magnet synchronous motor contains three sets of coils that are connected to the three phases of the power supply system. It is important to remind that the voltage / current source is an alternative source.

The stator currents produce a magnetic flux rotating in the same way as the flux production in a three-phase induction machine. [8] From this point of view, we can say that a synchronous motor with permanent magnets is equivalent to an induction motor, with the difference that the magnetic field in the gap is produced by a permanent magnet, one of the advantages of this configuration is the fact that the magnetic field in the rotor does not change over time, being produced by a permanent magnet so it is constant. Quantities such as flux, current and voltage are represented by spatial vectors.[9]. One of the most important aspects in synchronous permanent magnet motor technology is the electromotive force. The electromotive force in this type of motor is directly proportional to the magnetic flux and velocity, which means that the waveform of the electromotive force is the same as the flux density. Since the power currents are sinusoidal, they are also sinusoidal in shape. On the other side, this electromotive force is very important for controlling the machine. Synchronous machines with permanent magnets are generally controlled by the technique called vector control or flow-oriented vector control. Figure 2.4 shows the block diagram of the speed control of a synchronous motor permanent magnet.

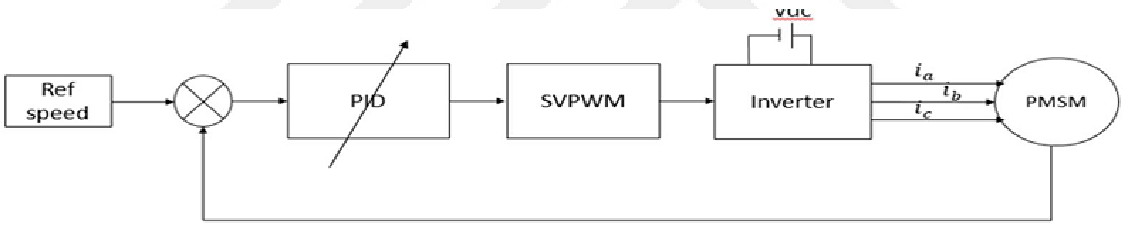



**Figure 2.4** Closed loop speed control of PMSM block diagram

In a closed-loop control, for the motor to be able to operate normally at high speeds, it is necessary to reduce the flux so that the electromotive force does not undergo any variation and remains at its maximum value. It is on this principle that the speed control of PMSM is realized. There are several control methods developed for effective control of these types of motors, but despite the difference in their mode of operation, the objective remains the same.

$$E_c = j.w.q \qquad \textbf{(1)}$$

Since the flux is constant under normal conditions, the speed therefore depends directly on the electromotive force. Equation (1) tells us not only about the importance of the electromotive force in the mechanical output quantity which is the speed but also the importance of the Back EMF in speed control.

Permanent magnet synchronous machines being electronically switched; the position of the rotor must always be known by a good electronic commutation. To estimate this position, methods are used, and among them, one of the most famous is based on the estimation of the value of the force against electromotive, which is induced in the stator coils.

### 2.3 Presentation of Direct Current Brushless Motors

#### 2.3.1 Introduction

In the first part, we have highlighted the synchronous machines with permanent magnets, which are also part of this family of electric motors without brush and whose switching of electric current is provided by devices of the power electronics. These machines are powered by three-phase sinusoidal electric currents, which is also the form of their induced electromotive forces. Having a fairly simple control compared to other electronic machines such as induction motors for example, and with the advantage of being able to operate in the most extreme conditions in terms of space or temperature conditions, the synchronous machines with Electronically switched permanent magnets are so present on the commercial market of rotating electrical machinery.

Like the Switcher Reluctance Machines, the synchronous machines with permanent magnets, to be adequately controlled, need to be provided with electronic sensors informing at all times of the mechanical position of the rotor of the machine [15]. This information allows to know which phase of the machine must be excited to ensure a successful electronic switching. The most often used sensors, are Hall effect sensors mounted so that they face a fixed magnet portion on the rotor and spaced from each other by an angle of 120 degrees. The advantage of using Hall effect sensors is that they are not expensive. The disadvantage is that in a situation in which a position check is made, the malfunction of a single sensor would lead to errors in electronic switching on the one hand and material damage on the other hand. It is from such considerations that another type of permanent magnet machine operating without brushes and mechanical collector has been developed. These machines have an induced electromotive force with a trapezoidal shape and are called Permanent Magnet Brushless Direct Current Machines (PMBDCM) or Brushless Direct Current Machines (BLDC), which is the abbreviation we will use.[13]

Thus, the advantages of BLDC machines are that, their control is not as complicated as synchronous machines with permanent magnets. Also, the sensors to Hall effect is not necessary to ensure electronic switching, which represents an advantage in terms of motor design as well as costs. [10]

### 2.3.2 Constitution of BLDC motors

Although BLDC motors represent the future of some areas of the industry, their constitution is not so special as shown in Figure 2.5. In terms of the physical characteristics of the winding in the stator, synchronous machines with permanent magnets have windings distributed in the machine. However, in a BLDC machine the winding inside the stator has a concentric structure. Just like synchronous machines with permanent magnets, BLDC machines have a mechanical torque which is, as in almost all electric motors, a function of current. The electromotive force BLDC machines being trapezoidal, to maintain a constant torque output, the machine is powered by a set of current whose shape is square.

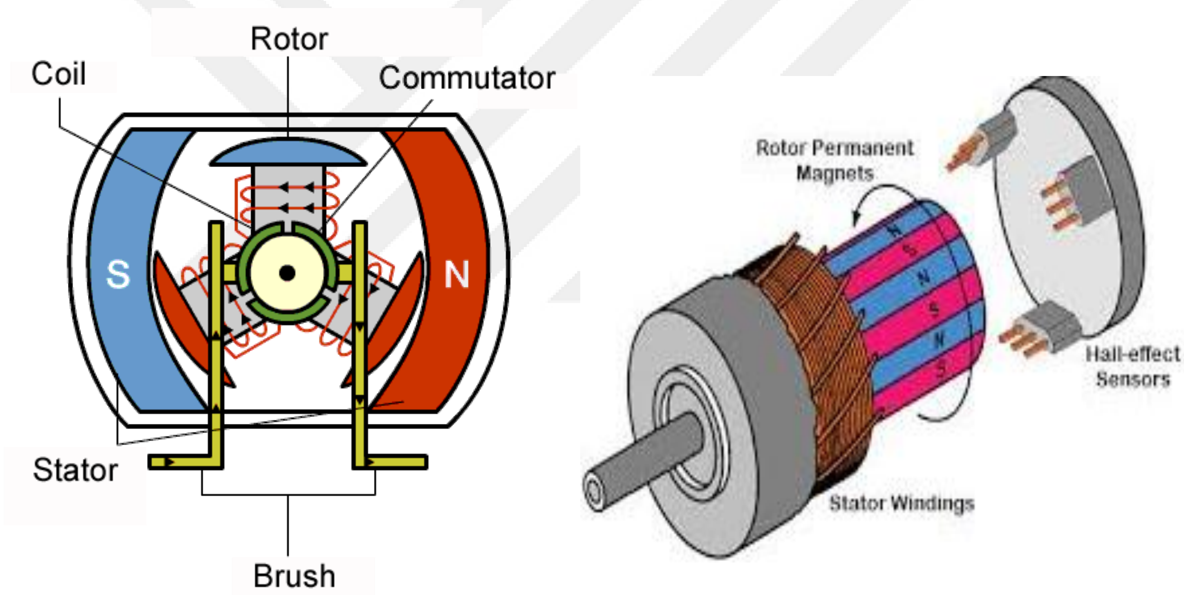



**Figure 2.5** BLDC Motor Configuration

The configuration of the BLDC motors is like that of conventional DC motors except that the BLDC motor as it is said is an opposite version of the conventional DC motor, that is to say the DC motor containing brushes and the mechanical switching system. The BLDC motor contains permanent magnets on the rotor and windings on the stator as shown in figure 2.5. The conventional DC motor does the opposite by having the windings mounted on the rotor and the permanent magnets mounted on the stator. The result of such a configuration is that most of the machine losses are in the rotor because the coil circuit limits the heat transfer to the stator through the air gap, which also influences the density of the current through the winding.

The advantage of the BLDC motor is to have an inverted structure of the conventional DC motor, which positively allows the dissipation of the bulk of the losses in the stator.

The BLDC motors are synchronous machines, that the rotor speed is perfectly equal to the synchronous speed $n$ of the rotating magnetic field of the stator. Not like asynchronous motors in which there is a parameter called slip g, which translates the gap between the synchronous speed $n_s$ and the actual speed of the stator n and which ultimately affects the speed that the motor can reach, n=$n_s$(1-g), the BLDC motors operate directly at the same speed as the rotating stator field, which has a real advantage over the speed range in which the motor can operate. BLDC motors are trapezoidally excited, they are excited by trapezoidal or rectangular shaped signal sequences.

#### 2.3.2.1 Brushless motor operating system

Brushless DC motors are mainly composed of three essential parts: the mechanical part that is to say the motor itself, an inverter system and a system whose role is to determine the position of the rotor, that is to say the motor shaft. [1]

#### 2.3.2.2 The BLDC Motors

From the constitution of the BLDC motor perspective, as briefly explained above, a BLDC motor looks like a DC motor in reverse. That is to say that the elements that form the rotor finally constitute the stator of the machine and vice versa. The BLDC motor is defined by the position of the permanent magnets on the rotor. The ways in which permanent magnets are mounted on the surface or inside the rotor define the characteristics of the operation of the motor as well as the different areas of application.

The most known rotor configurations are: The rotor magnet surface whose magnets are mounted radially or with a circumferential configuration.

The spike-type magnet rotor also has magnets mounted in a circumference configuration, with the only difference that this configuration provides an asynchronous start torque. The interior magnet rotor has a radial configuration of permanent magnets.[1]

The construction of BLDC motors is like the induction motor and the DC motor. As far as the operating principle is concerned, it is much closer to the conventional DC motor. Any electric motor has the function of transforming electrical energy into mechanical energy to produce a motor torque capable of causing any set in a mechanical movement whether rotation or linear. To do so, it is provided with two parts that are the stator which is the static part and the rotor, the moving part of the motor.

#### 2.3.2.3. The stator

The stator of BLDC motors is made of stacked rolled steel. It contains the windings of the machine. There are two possible configurations of the windings inside the stator. The first configuration can be a star configuration or mount and the second one is a triangle mount. This is similar to the induction AC motor. Compared to the characteristics and possibilities provided by these assemblies, a star configuration allows the motor to produce a high torque at low speed, however the triangle configuration releases a low torque at low speed.
The steel core can be melted at a pace. When this is not the case, in case of no slot, the inductance of the core is very low, and the motor can operate in a broad speed proposal including very high speeds. However, such a configuration requires the use of several bearings to compose the high dimensions of the gap.

#### 2.3.2.4. The rotor

The rotor of a BLDC motor contains the permanent magnets of the motor as shown in figure 2.6, which is not the case of the DC motor in which it is the stator which contains the permanent magnets of the stator. Each block of permanent magnets constitutes a magnetic pole. This number of poles is likely to vary from one motor to another and is related to the applications of the machine. The number of poles directly affect the speed of the motor. Thus, the number of permanent magnets will be determined according to the speed that is proposed to reach. A high number of poles produces a motor operating at low speed but having good torque characteristics.

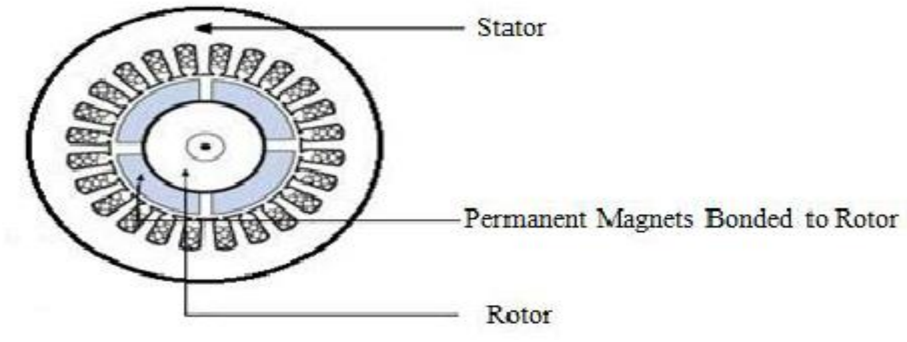



**Figure 2.6** Rotor and permanent magnets representation in front of the stator

A reduced number allows the motor to operate at high speed at the cost of a couple that must be monitored regularly.

#### 2.3.2.5 Inverter systems

Inverter systems would never have been possible without the progress of power electronics. Power electronics is seen as a branch of electronics in which the reflections focus on the development of electronic switches or systems containing increasingly powerful electronic switches capable of carrying currents of high intensities of up to one kilo or the mega amp. The use of such switches makes it possible to control the flow of current through an electric circuit and consequently supply receivers with a certain predetermined method. All electrical charges do not consume electricity in the same way [16]. Power generated by power plants supplies conventional electrical receivers with a constant and predetermined frequency. The use of electronic switches, by adjusting their switching frequency, allows certain special receivers such as BLDC motors to be powered at a frequency different from the frequency of the electrical networks. The operation of these switches also makes it possible to create a waveform of the signals used to power the machine.

### 2.4 Comparison between the BLDC Motor and the DC Motor

In a DC motor, there is a brush-collector system which provides switching, that is to say the change of polarity of the electric current. The collector is a rotating collector placed on the rotor, and the polarity of the flux is intimately related to the change of polarity of the electric current. When the electrical conductor passes through the flux, it automatically changes polarity when the polarity of the flux changes. The role of the collector is to synchronize the two polarities so that they change at the same time.

The change of polarity is necessary for the operation of the motor, so it remains essential regardless of the motor configuration. Since the flaw of the conventional DC motor is in mechanical switching, in a BLDC motor, the mechanical switching system is replaced by another switching system, which has the consequence of increasing the motor performance and reducing the risks of breakdowns.[1]

This switching system is a set of transistors, electronic switches of the power electronics ensuring the polarity change of the electric current depending on the position of the rotor. Between the electronic switches and the rotor is a system responsible for determining the position of the rotor and controlling the opening or closing of the transistors to produce the switching. In this type of switching, each frequency cycle *f*, the current changes polarity twice in one phase.

The particularities are that the electromotive force has a trapezoidal shape, the direct current remains constant during a switching interval, with a constant torque. In order to keep the torque constant, which is the role of switching, the current switches to another phase at the end of each switching period. This operation takes place during a conduction with square signals, which is the form of the signals of the BLDC motors. Permanent magnet synchronous motors have had conduction in which the waveform is sinusoidal as discussed earlier in the presentational section of the PMSMs.

The BLDC motor shows some interesting operating characteristics relating to its synchronism. Switching in the stator coils is closely related to the instantaneous position of the rotor, which means that the motor cannot lose synchronism easily even when the machine operates beyond the stall torque, hence the name of the machine auto-synchronous.

### 2.5 Domain of use of BLDC Motors

Due to their characteristics and known developments in the field of power electronics, BLDC motors have seen their popularity increase throughout time. The technologies invented with the use of inverters have allowed to power efficiently an motor which originally is a kind of continuous current machine.[13]

The possibility of BLDC motors to operate in constraining places and the known advances in the design of increasingly efficient electronic sensors have created a motor that would be called electronics and whose advantages compete with DC motors and with induction machines. All this has caused the demand for this type of machine to increase. For example, in the Chinese market the sales volume of 10Kw BLDC machines increased from 78 million in 2004 to 133 million in 2008 and this in 4 years only in China [13].

BLDC motors have a long service life, a high efficiency, a good torque-speed characteristic and make little noise.

•BLDC motors also find their application in the automotive industry with their power density which is very high, better than other types of known motors; good speed performance, good heat dissipation, which is very important for the automotive industry. In a context where an emphasis is placed on system design that can efficiently use energy, BLDC motors position themselves as considerable alternatives. [28]

•In aerospace, BLDCs have been used in the design of mini drones for example, the size of drones requires the use of small motors with good performance in terms of power density and low noise.

In addition, there are other examples such as hydraulic transmission devices that are being replaced by systems driven by electric motors. In this area too, there will be a strong presence of BLDC motors due to the advantage of their small size.

•As with the variable reluctance motors that are used in household appliances, BLDC motors also have a similar operation to reluctance machines. Variable, and find great satisfaction to be used in home appliances. Their benefits are in the low noise, good energy management and high reliability.

• BLDC motors are also used in office electronics such as hard disks, magnetic heads, CD / DVD players....

For a long time, DC motors were used for general and specific applications, not necessarily because they had exceptional characteristics but rather because there were no substitutes for this type of motor. The growing demands in industry and the disadvantages caused by the structure of this type of motor have led scientists to design electric motors without brush-collector system to reduce the risk of breakdowns and allow by their design the operation of this type of motor in very restrictive conditions. It is from these considerations that the brushless motors were created.

## 2.6 Inverter Systems Switches of BLDC Motors.

Electronic switches are semiconductors that control voltage, current, power, and frequency efficiently with the use of control systems such as microprocessors, integrated circuits, and integrator circuits large-scale.

The electronic switches used in the control of BLDC motors are diodes, MOSFET transistors and IGBT transistors.

### 2.6.1 The diodes.

A diode is known as an electronic device for driving the electric current under certain conditions. Firstly, it is a unidirectional switch, it lets the current flow in one direction. In addition to this, it contains two terminals including an anode and a cathode. When the potential of the anode is higher than that of the cathode, it lets the current flow. There is a voltage at which the diode starts to drive. This voltage is defined as the threshold voltage and it depends on the nature of the semiconductor used to design the diode. A diode contains a junction called PN, FIG. 2.8, a zone in which the doping varies abruptly from a P-doping to an N-doping. A depletion zone is created when the two junctions are implemented in contact. This zone arises because the electrons and the holes migrate on both sides and release a weak zone in charge carriers. The more the voltage applied on either side of the Pet N junctions reaches the voltage increases, the more the depletion zone becomes short and its resistance decreases which allows the passage of the electric current. The most used semiconductor is silicon and its threshold voltage is 0.7V. If the potential of the anode is greater than or equal to 0.7V, the diode conducts and is said to be in the state; passing. When the voltage is below 0.7V the diode automatically stops driving and is said to be the off state and the current through the diode will cancel. At the terminals of a diode, when it leads the voltage is 0V.

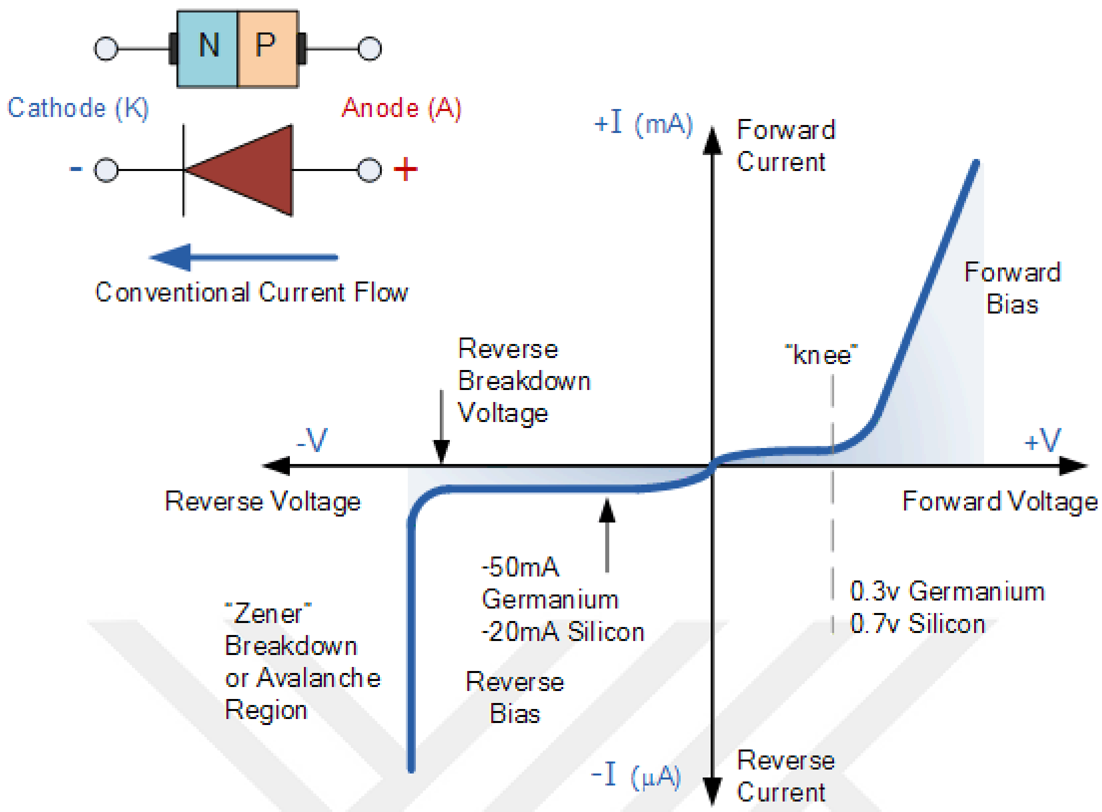



**Figure 2.7** Diode and characteristics with PN junction

When it does not drive, there is a certain voltage, which depends on the semiconductors used to make the diode, when the diode begins to drive, it can not hang automatically, it does have a kind of system self-regulation allowing it to hang on its own. To do this, it is essential to apply a negative voltage through its anode and cathode. The application of this voltage will polarize the diode in reverse and it will hang.

A very important parameter that determines the nature of a diode and its field of application is the reverse recovery time. It characterizes the time during which a current-conducting diode, to which an inverse voltage is abruptly applied for the blocking continues to conduct the electrical current from the cathode to the anode.

When the recovery time is less than a few tens of microseconds the diode is considered to be a slow switch. These diodes are used in applications in which their switching time is negligible compared to their conduction time. These diodes are called power diodes and can withstand voltages and intensities of the order of kilo ($10^3$). [10]

### 2.6.2 Mosfet

Not like diodes that are simple PN junctions, Mosfets are transistors in which the composition structure is quite different as shown in Figure 2.8.

They have two N curves and a P curve. They require very low voltages to drive and to be blocked. The characteristic of MOSFETs is their high switching frequency which ranges from 30KHZ to 1MHZ.

In applications related to the control of BLDC motors, the fact that the component behaves like a resistance in the conduction state gives the possibility that it be used as a current sensor. This feature reduces the costs associated with the machine and thus reduces the size of the machine so that the use of expensive systems such as Hall effect sensors or other types of current sensors is no longer necessary.

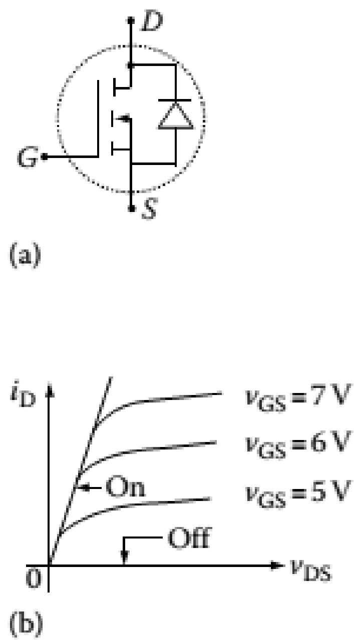



**Figure 2.8** Schematic of (a) N-channel MOSFET and (b) characteristics. (From Krishnan, R., Electric Motor Drives, Figure 1.5, Prentice Hall, Upper Saddle River, NJ, 2001.)

The basic structure of a MOSFET be a junction or set of three parts. First, there is a part called substrate which can either be a N-type dupe silicone region or a P-type doped region. Then, there are two small regions which if the silicone region is P-doped, they are N-doped and vice versa. These two regions called one the source and the other the drain. When the component is not polarized, it is impossible to differentiate between the source and the drain because the structure is symmetrical. The area beyond the source and the drain is called the channel area.

The overlapping part on the two regions, namely source and drain, is called gate. The MOSFET can therefore be defined as a component containing four terminals that are the gate, the following still called bulk, the source and the drain. When the potential of the gate is such that there is no inverting layer, the transistor is inactive. When the potential between the source and the gate $V_{gs}$ is positive and enough for the formation of an inverting layer, the reversing charges influence the source and the drain so that the channel current flows through the transistor. The condition of the passage of current through the transistor is conditioned by the application of a potential difference between the source and the drain this potential difference is called $V_{Ds}$. The great advantage given using the MOSFET is the possibility of controlling the current flowing through the transistor. The potential of the gate has an influence on the inversion of the charges. Consequently, and finally the current flowing through the channel is checked.

The voltage between the gate and the source is limited to 20V. Most often this voltage is kept constant at about 5V in order to protect the component from possible due to switching. The gate's potential is one of the most important voltages on the transistor. Thus, it is important to protect the circuits controlling the gate terminal. The circuits are protected against overcurrent, undervoltage and overvoltages. To get information on voltage and current values to protect the gate control system, current is measured from the voltage drop across the drain and source terminals. The voltage in turn is measured from the input DC voltage at the Converter [13] circuit. The Mosfet can conduct 100A current between voltages in the 100-200V range and 10A for 1000V voltages.

### 2.6.3 Insulated gate bipolar transistor.

The Insulated Gate Bipolar Transistor is a type of transistor characterized by a high input impedance and a large capacity to conduct current. The IGBT brings together some of the features belonging to the MOSFET. Typically, the IGBT has the MOS input characteristics and the output characteristics of the bipolar transistor as portrayed in Figure 2.9. We can therefore say that the IGBT is a combination of the MOSFET and the BJT. IGBT is used for high power applications. It conducts currents of 1.2 KA at voltages of 3.8 KV and currents of 0.6 KA at voltages of 6.6 KV.

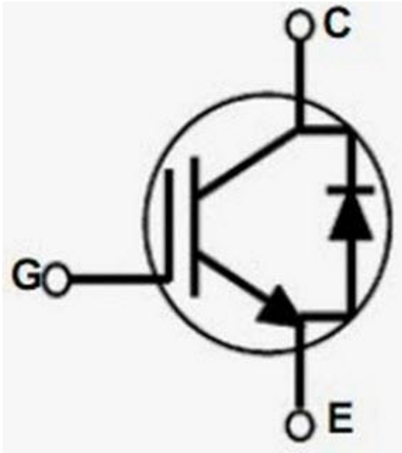



**Figure 2.9** IGBT symbol

In operation, the voltage drop in a transistor is around 5V. The IGBT transistor is also capable of driving currents of very high intensities at reduced voltages without causing high voltage drops. Less than the MOSFET, the switching frequency of the IGBT is around 20 KHz. The switching frequency of the IGBT is low for high power systems due to the occurrence of electromagnetic interference and switching losses when this is not the case.

## 2.7 Conclusion

Brushless motors as the name stand for electrical motors with brush are one family of electrical motors which work without the conventional electromechanical system that we find in electrical motors. They are provided with another type of system assuring the conversion of electrical energy into mechanical energy. This system is a commutation-based electronics system. Its used a certain logic to empower of energize the wind of the motor in order to provoke the rotation of the rotor.

# CHAPTER 3: BRUSHLESS MOTOR CONTROL

## 3.1 Introduction

Electric motors are machines, they are part of human achievements that can not technically have autonomy without the intervention of humans. Any machine is first designed for a need, then to perform a required function that solves the problem. Nowadays, there is a variety of electrical machines and they all meet specific specifications.

To adapt a machine to the needs of the user, the machine must first be designed to meet the scientific and technical requirements of the user. These requirements may include speed, motor torque, internal and external characteristics of the machine depending on certain parameters, the current consumed by the machine and the voltage system under which the machine should operate. The fact that machines do not have natural brains means that important notions of automatic are considered. One of the particularly interesting information is the **controllability** of the machine. Beyond the technical characteristics of the machine, it must be controlled by control devices that can be of various kinds.

Currently, in industry, it is impossible to find completely autonomous machines or that fits perfectly in industrial systems. To succeed in making work an electric machine and more precisely an motor in industrial processing sets, it is important to be able to control the machine. The elements that may be necessary for the control are the output and input indicators. That is to say, the machine must be able to react in adequacy with the state of the system in which it is installed. To force the machine to react so we use control techniques. [2]

Servo chains are interesting examples to better explain the concepts of control of electrical machines. To do this, let us take an example of a speed control of a DC motor as shown in Figure 3.1. Rotation speed is one of the most important output parameters to control on an industrial motor. A motor developing a very low speed may not be able to lift a load as a motor developing too high a speed can easily get off if the load is too heavy. Otherwise, it may just be necessary for the speed to be constant. In order to obtain the desired characteristics of the speed, it is necessary to have a margin of action on the parameters responsible for the variation of the speed of the motor. In a DC motor, the electromotive force is proportional to the actual speed developed by the motor. [3]

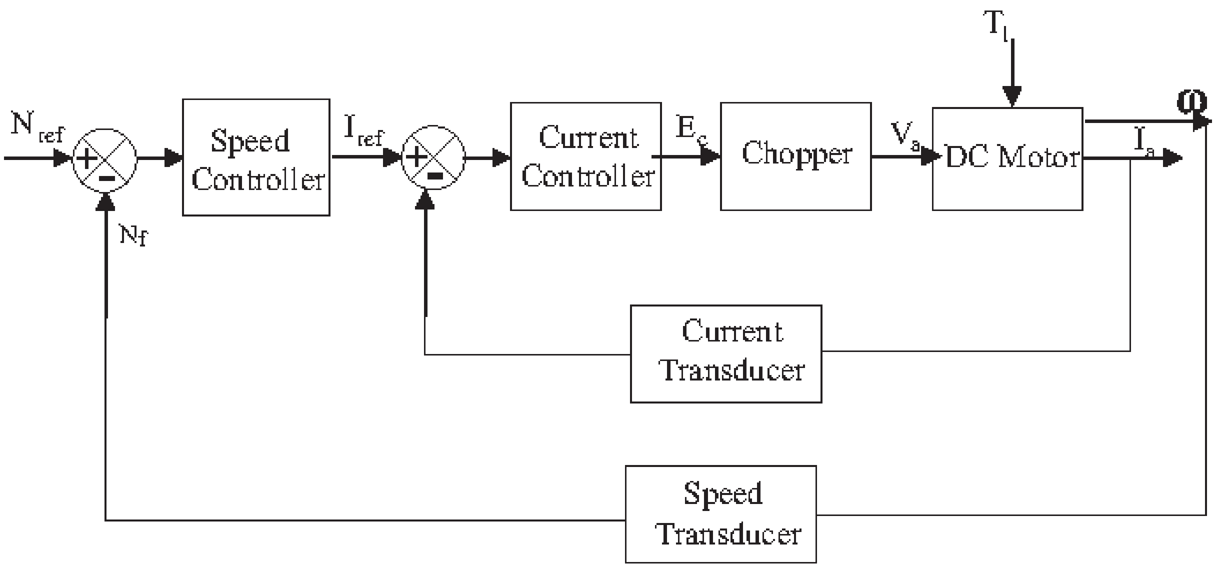



**Figure 3.1** DC motor drive block diagram

The electromotive force is itself dependent on the voltage applied across the motor. By a logical argument, it is clear that the speed of the motor is dependent on the motor voltage and that to act on this speed, whether up or down or to keep it constant, it is necessary to control the voltage applied to the terminals of the motor. Additional devices placed on the motor can not only vary the voltage at the terminals but also collect the necessary information on the value of the actual speed and compare it with the speed needed to reach. When this speed is correct, no correction action is taken and when the actual speed is different from the set speed, a correction action is taken. This type of servo control is in fact a control technique for DC motors.

### 3.2 Selectivity of Control of Rotating Machines.

In the field of control of rotating electrical machines, DC machines are the easiest to control because the electrical and mechanical equations of the machine are simple and better, they are linear, which greatly facilitate the task of realizing the system control. From another perspective, the type of control used to control an electric motor depends on the nature of the motor, its design and its field of application. When the modelling equations of the machine are nonlinear, in most cases, the control technique to use becomes very quickly complex and requires additional knowledge to achieve the desired objectives.

For example, the control of asynchronous motors has completely different characteristics from that of DC machines [4]. Not only the nature of the current used is different but also the equations for modelling the asynchronous machine are more complex than those of the DC machine. The effects of hysteresis for example will always be considered when we could for some needs neglect them in a DC machine. The vector control of the asynchronous machine or the flow-oriented control makes it possible to transform the typical equations of the asynchronous machine into an equation system qualitatively similar to the equations of the DC machine. This gives us an idea of the price of the actions required to be able to simplify the understanding of the inner workings of an asynchronous machine in order to better control it. As a reminder, the vector control was proposed in 1971 by the scholars Blashchke and Hass. This is a method that controls the speed variation of three-phase motors. It allows to transform the three-phase stator currents of AC electric motors into two orthogonal components which can be considered as vectors that allow one and the other to adjust the magnetic flux of the motor and to adjust the motor torque. [4]

The magnetic flux and the torque which, before the transformation, were completely connected are then separated after transformation, which qualitatively transforms the operation of the AC three-phase machine by making it like that of the DC machine. Indeed, the Park transformation allows to define a benchmark to understand and model, after study, the AC machine. The model thus obtained is like that of the DC machine. The various methods of controlling permanent magnet machines without brushes and electronically switched are logical but do not provide the same results with respect to the quality of the control. Moreover, the nature of the machine can quickly make the control very complicated.

There are two main methods for controlling permanent magnet brushless motors. A method called sensor control uses a series of sensors to obtain information needed to control the motor. The other method, which is sensorless control, uses another series of electronics to control the motor without using mechanical sensors.

The control using sensors is much more used for synchronous machines with permanent magnets. However, sensorless control is in turn much more used for so-called BLDC machines.

In the following lines, we will briefly present the control technique using the sensors and we will deepen into the technique that does not use sensors and more specifically in the field of BLDC machines.

## 3.3 Control Methods Using Sensor Technology

### 3.3.1 Hall effect sensors

The most common technique using sensors to control BLDC motors is the one using Hall effect sensors.

The Hall effect sensors, of the scientist Edwin Hall, are sensors that operate on the principle of Hall effect theory established in 1879. This theory shows that when an electrical conductor is placed in an electric field, the magnetic field tends to exert a transverse force on the mobile electric charge carriers of the conductor, causing them to propagate on one side of the electrical conductor. The result of this magnetic effect is that on one side of the electrical conductor, an accumulation of electric charges in motion is obtained while on the reverse side of the conductor, there is rather an accumulation of immobile electric charges. The Hall effect says that at this moment, there appears a voltage between the two sides of the driver. The particularity and the advantage of this voltage is that it can be measured. With regard to sensor control of BLDC motors, much like variable reluctance machines, their rotation requires information on the position of the rotor in order to be carried out properly. The information of the position of the rotor informs which winding is to be excited. In their case, the position of the rotor is determined by Hall effect sensors integrated in the stator. [11]

#### 3.3.1.1 Operation of Hall Effect Sensors

The motor being a three-phase machine, to determine the position of the rotor, three Hall effect sensors are placed on the stationary part of the machine, in the stator. When the rotor is rotating and its magnetic poles pass near the sensors, the latter react by giving signals to signify the passage of the magnetic poles and their natures. The information collected by the different sensors translate the position of the rotor and the exact sequence of switching is determined, at which time the corresponding winding of the stator is excited by an electric current. The position of the Hall effect sensors on the stator is so important because a bad position of the latter would lead to an error in the determination of the position of the rotor. The electronic controller controlling the opening and closing phases of semiconductors works closely with Hall effect sensors. In its principle of operation and according to the configuration of the motor, the commutation must allow only the conduction of two phases of the motor during 60 electrical degrees of rotation of the rotor. The Hall effect sensors are therefore mounted in a range of 60 degrees electrical relative to each other. [12]. The most interesting controls for electric motors are the speed, position and torque controls. In the speed control for example, as seen above, it is possible to control the motor by the control technique using sensors (Hall effect for example). Beyond this method, there are still other methods that also allow to obtain satisfactory results. Among these methods, a particularly interesting one is the PID control.

### 3.3.2 Theory of PID control

PID control is one of the most successful linear control systems for controlling industrial systems. This control is most often used for servo drives. The PID regulator is a combination of several other regulators that are not widely used in the industrial field. The actions of these controllers are the proportional action for the P, the integral action for the I and the derivative action for the D. Figure 3.2 showcases the block diagram of a PID controller. We can notice the combination of different regulators to form a single regulator.

**•Advantages and limitations of proportional, integral and derivative actions.**

**•The proportional action** influences the gain of the transfer function of the open loop, allowing to obtain a more precise system, a faster system. The disadvantage of this action is that one gets a less stable system [27].

**•The integral action** has the advantage of reducing the actual measurement at the output of the system to the setpoint value required during the design of the system. It removes the residual value between the actual measurement and the setpoint. The disadvantage of this action is a decrease in the stability of the closed-loop system.

**•The derivative action** helps stabilize the system, it is in fact a corrector of the integral action. Nevertheless, it has the disadvantage of increasing high frequency noise settings.

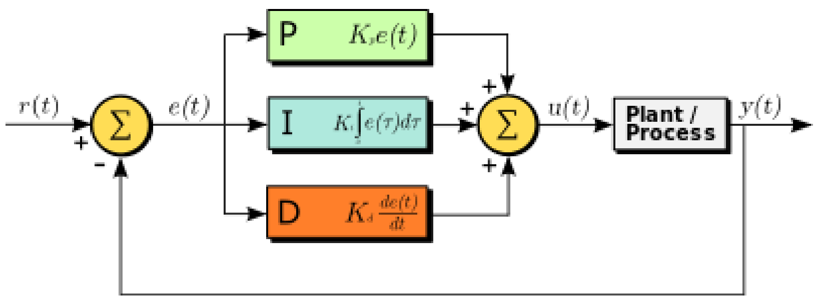



**Figure 3.2** PID Controller block diagram

The advantage of the PID regulator is to combine all these advantages and to reduce the defects of each of these regulators. As a result, a simple, robust, reliable controller with the ability to easily adjust the parameters is provided. The following equation is the control law of a PID [13]

$$u(t) = K_p \left(e(t) + \frac{1}{T_1}\int_0^t e(t)\,dt + T_D \frac{d\,e(t)}{dt}\right) \quad (1)$$

In its operation process, the PID determines the difference between the setpoint value e (t) and the actual value at the output of system y (t). When this is determined, the regulator control law is used to cancel this deviation to obtain the set value at the output of the system.

$K_p$ *est le gain proportionnel*

$T_1$ *est la constante de temps du correcteur intégrale*

$T_D$ *est la constante de temps du correcteur dérivé*

### 3.3.3 Evolution of PID control

PID control technology has improved over time and according to the characteristics of the systems to be controlled. There are several types of PID controls. PI, PD systems are also part of the structural forms of PID systems that may exist. It is true as we have seen above that the different proportional, integral and derivative actions have disadvantages when they are used alone to control the systems. The combination of different actions brings benefits although there are always disadvantages [27]. All these combinations are part of the family of PID controllers. For instance, PI control has significant advantages and is one of the most used control systems in the control of BLDC motors. The disadvantage is that this control makes the system subject to disturbances caused by high frequency. Techniques using digital electronics have therefore been developed to overcome these errors. By discretizing the basic modelling equations of the normal PID controller, we obtain a digital PID controller with a new control law seen as a position control algorithm using PID technology. Figure 3.3 shows a digital PID controller served as a model.

$$U(k)= k_p \left[e(t) + \frac{T}{T_I}\sum_{j=0}^{k} e(j) + \frac{T_D}{T}\big(e(t) - e(k-1)\big)\right] \quad (2)$$

$$= \; k_p e(t) + k_I \sum_{j=0}^{k} e(j) + K_D \big(e(t) - e(k-1)\big)$$

$k_I$: Integral coefficient

$K_D$ : Differential coefficient

$T$ : Sampling period

E (k) and E (k-1) are deflections to inputs at respective times kth and (k-1) th

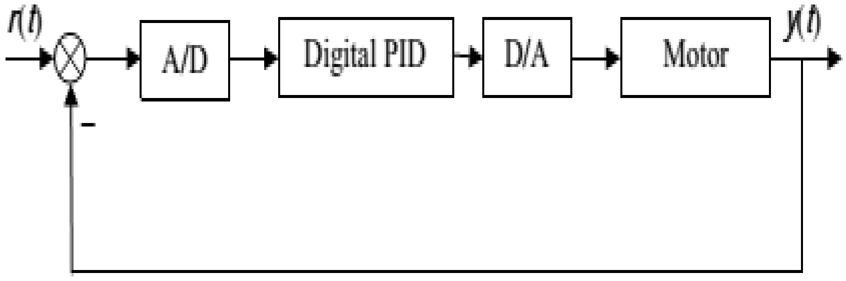



**Figure 3.3** Diagram of the digital PID motor control system [13]

- ❖ The disadvantage of this method is that the dynamic performance of the system is not high and there are high errors between the actual values and the set values. Thus, the discretized law is transformed into a recursive law. [13]
  The design of such a structure to improve the performance of the control of the BLDC motor implies to take into account several parameters: those related to the motor concern the environment in which the motor evolves, the methods used to determine the position of the rotor and also the characteristics of the load to be connected to the motor, those related to the digital PID controller are the proportional, integral, derivative and sampling period parameters. Parameters P, I and D are determined by tests whose purpose is to find at the same time the necessary settings resulting in a stable response of the system, a static stability and a fast-dynamic response.[14]
- ❖ The control of BLDC motors today is based on a two closed loop P controller technique, an inner loop and a closed loop. This technique aims at stabilizing the current and minimizing the effects due to the variation of the voltages, which is the role of the internal loop of the controller PI. The outer loop aims to stabilize the speed by minimizing the resistant effects of the connected load. The discretization methods and the recursion laws applied to the basic equations of the PID controllers allow the design of digital PID systems whose characteristics are more advantageous than the basic PID controllers. The benefits include:
- ❖ More flexible control, greater accuracy in control, and the ease of using very complex algorithms.
- ❖ A drastic reduction in the effects of disturbances.
- ❖ Greater ease to be inserted into sets using high digital technologies and communication network.
  The result is a reliable and satisfactory speed control.

However, the development of several other kinds of PID not only warns that it is necessary to look for the PID required for the control application but also that each PID still has advantages and disadvantages that future PID seeks to correct [14].

### 3.3.4. Smart controllers

As we have seen above, the search for optimal control of BLDC motors has led to the creation of several control techniques which up to now have their share of advantages and their set of disadvantages as well.

To continue to improve control of BLDC motors, methods using intelligent controllers, which were originally part of the control methods used in biology and immune system studies, are beginning to gain prominence in the domain of control of BLDC motors. [14] In essence, intelligent controllers use methods derived from the theory of automatic control and theories of artificial intelligence among which we can find genetic algorithms, fuzzy logic, networks of artificial neurons. These control methods are not based on mathematical methods exclusively but on logical approaches that sometimes consider subjective concepts such as uncertainty concepts, environmental constraints that can be very complex to evaluate mathematically or to model. The fuzzy logic for example takes into account all these considerations, which constitute the limitations of the control systems usually used. The systems usually used rely too much on the mathematical modelling, which constitutes the point of reference of the control initiated. For instance, the control method with Hall effect sensor very strongly depends on the mathematical model. [14] Although it may be a logic capable of solving the problems encountered in the conventional control of BLDC electric motors. The control systems using the fuzzy logic present a great difficulty in being able to adapt to the new information while the control systems based on neural networks have the ability to adapt to new rules and thus prove to be solutions for solving problems related to mathematical models of the system (problems of uncertainty and disruption). Genetic algorithms have demonstrated an ability to improve the capabilities of control systems improving the results obtained during the controls.

Just as the P, I, D structures that have disadvantages but become very powerful when in combination, for example, PI, PD, PID, intelligent controllers have remarkable capabilities when operating in combination. For example, a combination of fuzzy control and artificial neural net produces a fuzzy neural network controller with the ability to reason better and learn, while in a separate way, a fuzzy controller learns less well and reasons better when a controller-neural network does the opposite. The combination of the two logics of control would logically fill the limits presented by each controller. Such an association is just one example of all the combinations that can be obtained depending on the needs of the control. In the following lines, we give more precise information on fuzzy control, neural network control and control using genetic algorithms applied to BLDC motor control applications.

#### 3.3.4.1 Fuzzy control systems

The fuzzy control is a control that requires few mathematical equations. Namely, it depends very little on the mathematical modelling of the system to control. Fuzzy controllers are intelligent controllers made up of a part of fuzzification that fuzzifies the input information, a database of information, a logic calculus admitting propositions related to real propositions called fuzzy inference, a defuzzification system, and finally the system to control. Its advantage is its independence to the equations of the system to control. This independence gives it great adaptability and robustness. In addition to this, the ability of fuzzy reasoning systems allows them to consider information that is not known beforehand. Figure 3.4 portrays a control using fuzzy logic.

The fuzzy controllers are divided into three major parts: standard fuzzy controllers, fuzzy-PID controllers, and improved fuzzy controllers. All three categories are actually different methods based on fuzzy logic to control BLDC motors. Fuzzy control systems prove to be good speed regulators and are effective in non-linear control. [14-18].

**The standard fuzzy controllers**

These are controllers that operate on the basic principle of fuzzy controllers. The dynamic performance of this type of controller is low. In addition to that, the dimensions of a standard fuzzy controller do not exceed 3. This is due to the complexity of the control algorithms.

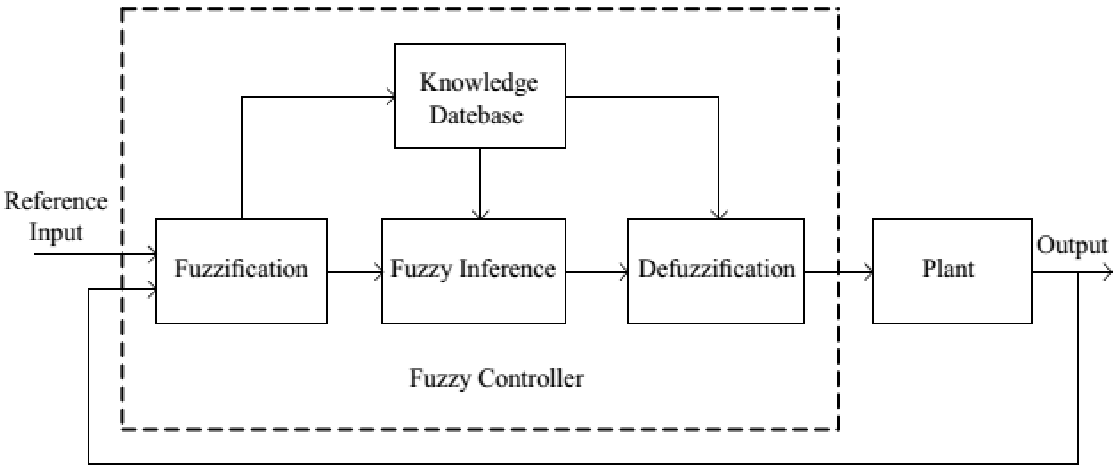



**Figure 3.4** Typical diagram of a fuzzy-control system. [13]

**Fuzzy-PID controllers**

In this type of control, a PID controller associated with a fuzzy controller is used. The control of the system is largely carried out by the fuzzy control. The PID controller only works when the fuzzy controller output signal is zero.

**Improved fuzzy controllers**

This is a method that improves the functions of a PID controller by using the operating rules of a fuzzy controller. The controller operates online and its parameters are set according to the state of the system to be controlled.

### 3.3.4.2 Control systems in artificial neural networks

These are control systems whose functioning is based on the typical functioning of the human brain. Today, these systems have been applied to the control of several types of electric motors including BLDC motors. This type of control system is particularly used in speed control, current control and position control. Since BLDC motors are non-linear electrical machines, it is no longer necessary to notice the control complexity of non-linear systems. The standard control of electric motors relies heavily on equations modelling the system to be controlled [21]. The disadvantage of such an approach is that it is very difficult to determine an exact mathematical model, there is always some uncertainty in the model. This has a great influence on the design of the controllers. For instance, PID controllers have constant gains and have great difficulty in actively responding to changes in the motor during operation. These changes may be variations in the load, the internal resistance of the motor due to heat for example or other environmental conditions. PI, PID and other regulations do not predict such changes and therefore may become useless in the control of nonlinear systems like BLDC motors for example.

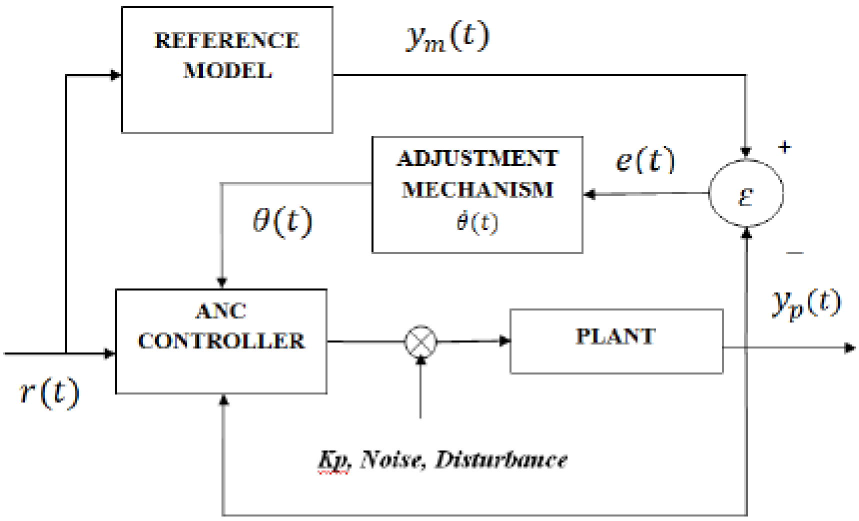



**Figure 3.5** Block diagram of a model reference adaptive control

The limit of the PID controllers reveals the need to design another type of controllers that can adapt to external conditions. One of these solutions, apart from the fuzzy logic, is control using artificial neural networks, sometimes referred to as the reference method adaptation system.

### 3.3.4.3 The adaptive control technique to the reference model

It is a control technique that results of the control theory based on artificial neural networks. This technique consists of a control system in two loops "Closed", an internal and an external, whose parameters are set according to the behaviour of the system to be controlled to follow a reference model as shown in Figure 3.5.

The advantage with intelligent controllers in this category is their advantage to understand and consider the information from the system to be controlled. They also excel at controlling non-linear systems like BLDC motors [23].

The reference model is a model that gives the desired answers during transitional periods. The transient response given by the system in real time will rule whether the system follows the law taken as a reference model or not. [19]. The control system using the neural reference model works with two artificial neural networks: the controller network and the network identifying the structure to be controlled. The operating principle of this type of control is to determine the model of the structure to be controlled.  intelligent system of the controller comprises the structure to be controlled so that the output signal of the latter follows the output signal of the reference model.

### 3.3.4.4 Optimized control system using genetic algorithms

Genetic algorithms used in BLDC motor control applications provide much more control. Generally, they are used in speed control applications requiring high accuracy. The genetic algorithms consider the different operating states of the system to be controlled and improve the control rules of the BLDC motor. [20-24]

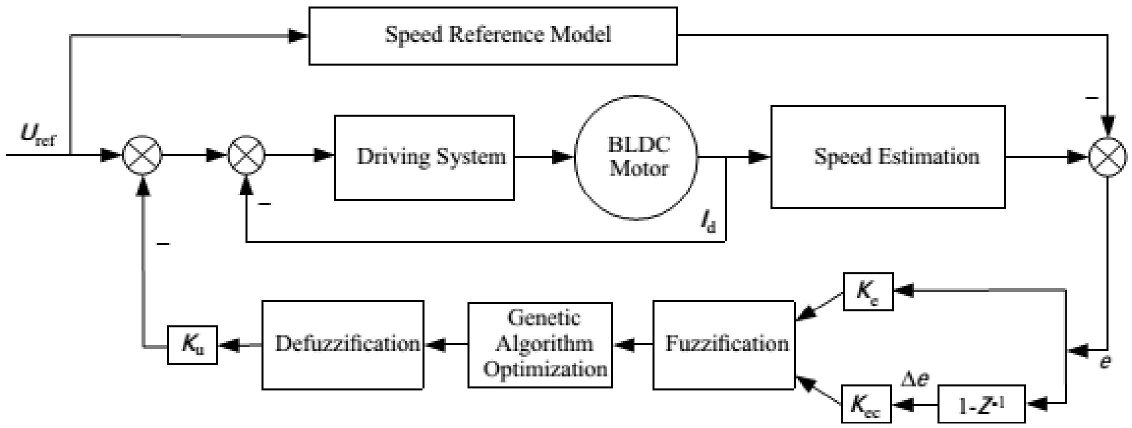



**Figure 3.6** Fuzzy controller coupled with a genetic optimization algorithm

Being used to improve control systems as shown in Figure 3.6, they are used to improve control systems using fuzzy logic. In response to the non-linear nature of BLDC motors, fuzzy controllers coupled with genetic algorithms improve the performance of the controller thus created. The performances that this association of control logics bring are among others the stability and the quality of the control which are quite satisfactory.

### 3.3.5 Determination of the performance of fuzzy controllers

The fuzzy controller's performance is determined by the controller's ability to reason in real situation and this ability depends on the fuzzy controller programming, how it is designed to reason, to respond to emerging situations in the environment.

Two important parameters determine the performance of a fuzzy controller: these are the scale and quantization factors. [13]

In general, the scale factor and the quantization factor are fixed and therefore can not vary in real time. This feature limits the performance of the controller and makes it less able to adapt to changes in the characteristics of the system to be controlled. To solve this problem, we insert in the fuzzy controller's control rules some analytic expressions to obtain coefficients that can be set or correct when the BLDC motor is running.

To enable this task, factors corresponding to the various errors returned by the scale factor and the quantization factor are used. The quantization error factor $K_{e_1}$ and quantization change error factor $K_{e_c}$ make it possible to adapt the fuzzy controller to the change of the system. Finally, the scale factor $K_u$ transforms the values from the fuzzy control so that they are converted for use on the system to be controlled [24].

All these three parameters $K_{e_1}$, $K_{e_c}$ and $K_u$ have an influence on the response of the system, which is closely related to the values of these different parameters, which is why their choice is judicious and to consequences on the system.

The choice of the parameter values is done considering the fact that :

First, $K_{e_1}$ has an influence on the speed of response of the system. The larger $K_{e_1}$ is, the faster the system reacts. The smaller $K_{e_1}$ is, the slower the system convergence rate will be. However, too much $K_{e_1}$ would cause large overruns.

- Similarly, $K_{e_c}$ influences the response of the system. More $K_{e_c}$ is large more the response of the system is slow. The smaller $K_{e_c}$ is, the greater is the risk of oscillations.
- Finally, $K_u$ is the most influential factor on the system's response. $K_u$, is the proportional gain of the controller. A great value of $K_u$ would also have a great influence on the speed of the system to respond. A large value of $K_u$ makes the system faster. A low value generates strong oscillations of the system.

The adjustment of these parameters can only be done in a precise way in theory. In practice, two parameters are determined and the third is determined according to the responses of the system. We therefore carry out tests to determine its value which appears only as an equilibrium value[24].

After determining the parameters, we obtain a system with a satisfactory response, satisfactory static and dynamic performance of the fuzzy controller. The only problem is that the parameters $K_{e_1}$ , $K_{e_c}$ and $K_u$ are never satisfying in the long run taking into account the fact that they are static. Thus, it is necessary to adjust them online using a method that takes into account the static error of the dynamic system.

### 3.4 Sensorless Control Methods

In the field of sensorless control, there are also several techniques that have been developed, each with its advantages and disadvantages. Their common advantage is to significantly reduce the manufacturing cost of the machine and to make it more reliable by reducing the number of breakdowns due to the presence of mechanical sensors, such as Hall effect sensors for example, and drivers used for the different connections. They also allow the machine to evolve in places binding or heat for example could damage the electrical conductors or the operation of the sensors.

It is possible to wonder why we speak of control without sensors whereas in the control system, there are indeed devices serving as sensors. In fact, there are some applications in which rotor position information does not need to be accurate and only electrical measurements are needed: this is called sensorless drives. The BLDC motor, by its nature, collects information from the rotor position directly on its terminals.

Among the most widely used methods in sensorless control, one is the most common one called electromotive force sensing. [17]

During the operation of the motor, just two phases lead at the same time, which means that there is a phase in which the electric current does not circulate. The method of electromotive force detection is to use devices that detect the moment when the electromotive force in the nonconductive phase is zero. This moment permits to determine the switching times in the stator coils. Once this moment is detected, the microcontroller switches the conductive phases by controlling the electronic switches responsible [35] for the conduction of these electrical phases.

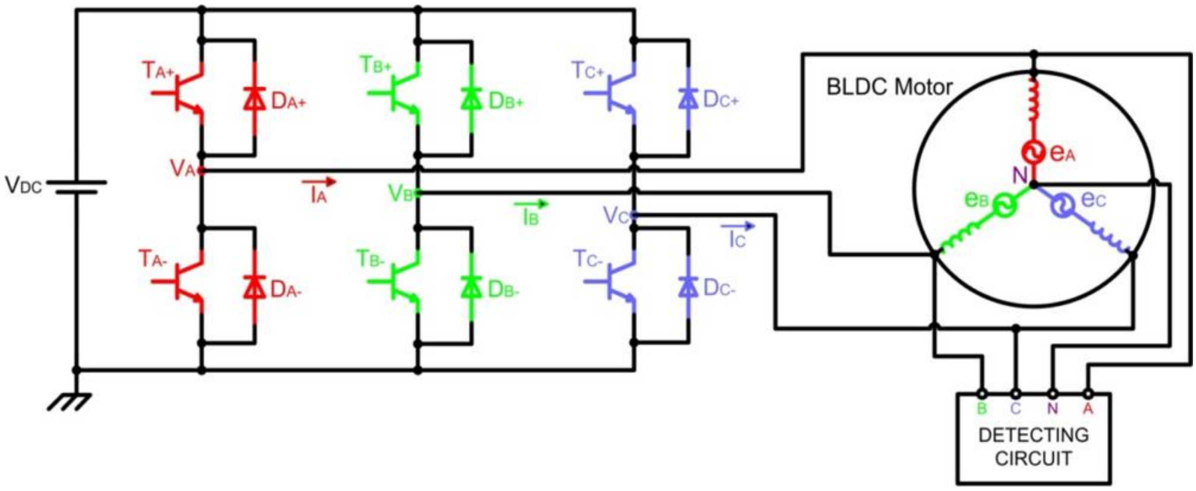



**Figure 3.7** Typical Diagram of a Sensorless Control System [1].

In sum, two phases always conduct to the same moment and the non-driving phase is used to detect the electromotive force. This is cyclically ensured so that the motor is always powered. Figure 3.7 shows the typical diagram of BLDC motor training by the control method without. It can be discerned that the complete system consists of an inverter acting as a switching system, the brushless motor itself, and a system for detecting the position of the rotor. There are two methods for detecting electromotive force in a BLDC motor. A method called direct electromotive force detection method and another method called indirect method of electromotive force detection. In the following lines we will talk about these methods.

**The direct method of electromotive force detection** is to detect the moment when the electromotive force of the non-conducting phase vanishes. This method is also called zero detection, electromotive force against. It is classified in two parts which are:

- Zero-crossing detection (ZCD) also known as Terminal Voltage Sensing
- The PWM control strategy.

### 3.4.1 Terminal Voltage Sensing

This technique as mentioned above is to detect the moment during which the electromotive force against the inactive phase is cancelled. The detection of this instant by an appropriate system triggers a timer whose end of the count generates the following switching sequence. Two phases are used to obtain the information concerning the electromotive force against. As a result, the microcontroller accurately determines the instant of phase switching within the stator. Not to mention that the role of switching is to produce a constant and maximum torque, in the case of BLDC motors, it is necessary that the electromotive force and the conductive phases of the electric current are aligned, and also the inverter system must switch all the electrical 60 degrees as soon as the zero of the electromotive force is detected. Figure 3.8 shows the different phases of the motor when it is in operation, it can be seen that the moments when the electromotive force goes through zero and the switching times do not occur at the same time. Typically, they take place after a certain time corresponding to 30 electrical degrees.

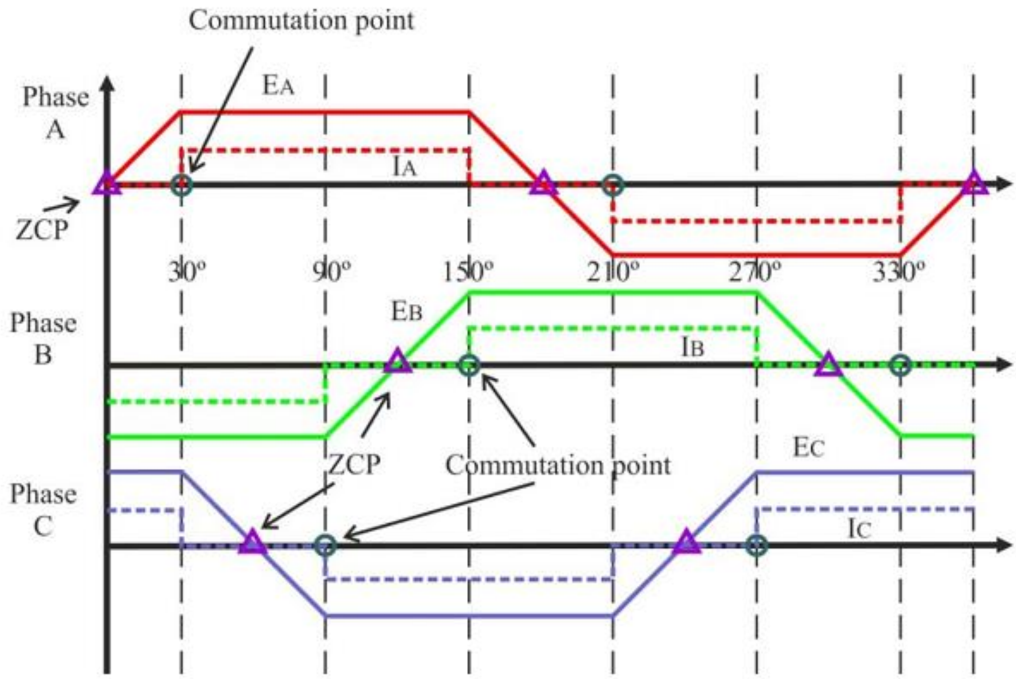



**Figure 3.8** Phase current switching and Detection Zero Crossing Points of the EMF Back [1]

The commutations generated by the inverter system produce harmonics. The amplitudes of the different harmonics being different. It is necessary to eliminate the highest harmonics because they have negative consequences on the operation of the machine. For this purpose, low pass filters are placed on each phase of the stator to eliminate the highest harmonics. The consequence of the use of these filters has a negative impact on the speed range of the machine which finally can not operate at high speed [1].

Studies show that the electromotive force reaches its zero when the voltage of the phase that does not conduct the electric current is equal to half of the DC voltage applied to the motor. [20] Concerning the strategy to obtain the zero of the electromotive force, the low pass filters can be replaced by a pulse width modulation system (PWM). One of the first benefits of this integration is the elimination of the negative effect that low pass filters have on the motor.

By using a PWM strategy, it is no longer necessary to create a virtual neutral point to extract the electromotive force [1].

### 3.4.2 Third harmonic integration method

In this method of detecting the instant of switching, it is assumed that the motor contains electrical phases connected in a star. Then, the third harmonic of the electromotive force is used to determine the different switching times. The technique is based on the fact that if the distribution of the flux in the gap is trapezoidal; then the sum of the voltages of the different phases equilibrium and the harmonics such as the fifth and the seventh harmonic are also cancelled, which is not the case of the third harmonic which keeps a constant phase. The advantage of using the third harmonic is that there is a reduction of filtering, the delays caused by the filters have no problem and the machine operates at high speeds. This means that the speed range in which the machine can operate is relatively large. The third harmonic method makes it possible to easily estimate the position of the rotor flux, which favors switching and allows more efficient and appropriate current control. Also, in comparison with the electromotive force zero detection method, in which it is very difficult to determine the zero crossing of the low speed electromotive force, the third harmonic can be detected at low speed. [29]

In addition, the components of the harmonics of the air gap of the machine depending on the rotor magnets and the stator winding, in the case where the phases of the inductance are constant, whatever the position of the rotor, it is possible to measure the third harmonic of the electromotive force. Referring to FIG. 3.7, the sum $V_{SUM}$ of the voltages of the different phases containing only the third harmonic and its multiples, the voltage which contains the third harmonic is filtered and integrated in order to estimate the leakage flux of the rotor. The leak flow estimate provides the necessary information to ensure switching when needed.

$$V_{SUM} = V_{AN} + V_{BN} + V_{CN} \approx (e_A + e_B + e_C) \approx 3E_3 \sin(3w_e.t)$$

$$\measuredangle_{r_3} = \int V_{SUM} dt$$

These two expressions give us, for $V_{SUM}$, the expression in which we obtain the measurement of the third harmonic and the moments of commutation. Studies show that the third harmonic component of rotor flux $\measuredangle_{r_3}$vanishes at 60 degrees electrical and that this corresponds exactly to the moment at which the switching must be carried out in the stator. In order to detect the component of the third harmonic in the case of an operation of BLDC motors without sensors, the third harmonic component is extracted by exploiting the voltage between S and the midpoint H of the DC bus. [30] Of course, an open-loop start procedure is necessarily used and the stator resistors are connected in a triangle to allow the third harmonic component to be detected.

Improvements have been made on this technique. For example, an air compressor needs to start with a fairly small torque. When starting in reduced torque, the switching has a delay time during high speed operation. For this purpose, a Phase Locked Loop (PLL) is used in which

freewheel diodes conduct just after switching and an inverter system is responsible for reversing the voltage measured across the stator. The integration of the third harmonic of the electromotive force instead of the voltage across the stator therefore allows to reduce the switching delays and thus improve the performance of the motor.
The advantage of this technique is that even at low speed, it is possible to detect the signal of the third harmonic and trigger switching, which is not possible when using the force zero detection method against electromotive. Indeed, the electromotive force against being proportional to the speed, a low speed generates risks of the false zero of the force against the electromotive, which makes the detection very delicate at low speed.
Applications using this method are in the domain in which high speed operation is required. The ease of implementation of the PLL system, the robustness of the system and low sensitivity to the production of electrical noise are great advantages. The technique can also be used in systems that require these benefits as an operation requirement.
The method of indirect electromotive force detection comes to correct the problems encountered when using the direct electromotive force detection method. In the following lines, these methods are explained in detail.

### 3.4.3 Terminal Current Sensing

This technique uses power transistors and freewheel diodes mounted in antiparallel. The conduction state of the freewheel diodes informs about the passage of electric current in a phase. This current comes from the electromotive force produced in the motor winding. Thus, when the current conducting phase is active, the conduction signal of the phase is collected at the level of the power transistors. In this technique, the line current of the motor must be in phase with the signal of the electromotive force, in this way the produced torque is maximum [1]. It is necessary that the switching action be performed every 60 electrical degrees. Although, requiring a start-up circuit to indicate when switching is required for start-up, the advantage with this technique is that the rotor position can be easily detected in any speed range, whatever at high speed, the conduction condition of the diode on the negative side is that $e_c$<0.

The disadvantage is that the technique does not work on a machine whose stator winding inductions do not vary with the position of the rotor. This condition is achieved with the SMPM Motors but impossible with the IPM Motors.

One of the disadvantages is that it is impossible to detect the position of the rotor when the motor is stopped. The current of the open phase comes from the electromotive forces, which requires an adequate starting procedure. [19] This method is only used for low speed applications. And the disadvantages are in the fact that additional devices are needed to detect the circulating currents in the freewheeling diodes. As a result, the method is therefore little used in practical applications.

### 3.4.4 Back-EMF Integration

This method uses the information of the electromotive force of the unexcited phase to determine the switching times. The electromotive force is integrated when the electromotive force of the unexcited phase crosses zero. The phase current is switched when the integrated value of the electromotive force reaches a predefined value [1]. This value corresponds to a switching point. The advantage of this method is that it supplies the system with the characteristic of being less sensitive to interference from switching and adaptability to changes of speed except for low speed applications that are problematic for this type of techniques.

### 3.4.5 Using the MLI Method

Pulse width modulation, abbreviated MLI, is one of the most widely used techniques for controlling the output AC output currents of electronic power converters. The pulse width modulation enables to vary at high frequency the duty cycle of the converter switches to obtain desired currents or voltages at low frequency [1]. The most important in the power converters being the characteristics of the output quantities that is to say the current and the electric tension, the use of the MLI had much more appreciation than the semiconductors because of the fact that converter circuits using semiconductor-based switching types only work at all. Characteristics such as switching frequency, harmonic output, losses, and response time should be considered in the development of modulation strategies. The MLI provides a fundamental frequency voltage and eliminates the highest harmonics in a considerable way.

In methods for controlling BLDC motors, there are several techniques that use MLI strategy to achieve high performance. These methods include the conventional 120-degree method, virtual neutral point elimination, techniques for low speeds and high speeds, and low power applications.

#### 3.4.5.1 The conventional MLI 120 degree technique

This is a technique in which the inverter system is controlled with the help of a method using pulse width modulation. The system switches all 120 degrees and the advantage results in a loss reduction on the inverter side. The disadvantage is the production of many harmonics of high amplitudes [1].

### 3.4.5.2 The virtual neutral elimination technique

This method is based on the techniques already studied. Indeed, as we mentioned above, the aim is to determine the instant of phase switching in the motor. The motor contains three phases and cyclically, one of the phases is inactive when the other two conduct the electric current needed to always have the desired torque.

To detect the electromotive force in order to achieve good switching, a virtual neutral called point is used, to determine the potential difference between the floating phase and the virtual neutral to detect when this voltage cancels. This potential difference corresponds to the electromotive force of the inactive phase [1].

Virtual neutral elimination is achieved using filters. The zero crossing of the electromotive force is detected by measuring the voltage across the idle phase compared to the ground using the proper PWM strategy. By applying it to the switches in the upper part of the converter, the strategy is to detect the electromotive force just at the moment when the MLI is not working, that is to say inactive. It is at this moment (period) that the relationship between the voltage of the non-conductive phase and the electromotive force is such that: $V_c = \frac{3}{2} e_c$

This method allows to get a large margin of speed and can also be used in high and low voltage systems. It finds its application in fuel pumps for vehicles, compressors and vacuum machines.

### 3.4.5.3 The technique for low speed or low voltage applications

It also presents its challenges when the voltage is low, there are losses in the electronic switches, which has negative repercussions on the motor performance. As we know, mechanical characteristics such as speed have a direct link with the voltage across the motor. The lower the speed is, the lower the tension is. At low speed, it is almost impossible to detect the magnitude of the electromotive force [22].

To be able to detect the instant of switching, one uses either a PWM strategy or one eliminates the voltage losses related to the conduction of the diodes.

The use of PWM strategy reduces heat-related power losses in the diodes. In this technique, for low voltage applications, the voltage of the phase not conducting the electric current is determined when the switches that are placed above are in idle state and the current flows through the wheel diode D. Studies [28] show that the voltage across this phase is such that: $V_c = \frac{3}{2}e_c - \frac{V_D}{2}$

At high speed the voltage $V_D$ does not affect $V_c$ and therefore the zero crossing is easily detected. However, at low speed the term $V_D$ affects $V_c$ because the electromotive force against $e_c$ being related to the speed is very low.

#### 3.4.5.4 The technique for high speed or high voltage applications

It uses a microcontroller whose role is to allow switching within the three phases. The three-phase operating circuit feeds the microcontroller, but their current is limited using three resistors placed on each phase. The RC time constants of the resistances controlling the passage of current in the microcontroller being long, they cause false switching. In high voltage applications, to achieve successful switching, it is necessary to accurately detect the zero crossing. The discharge time of the RC circuits is reduced by using resistors of very low values connected in parallel with the resistors limiting the phase currents. Throughout the operation of the system, the duty cycle used in the MLI strategy is very high. A diode is placed on the branch circuit of the additional resistor to block the currents from the discharge of the RC circuits. This technique allows, for example, motors using 300V / 30000rpm voltages to reach high speeds to operate efficiently[1].

#### 3.4.5.5 The technique for low power applications

This technique also uses a PWM technique for motor control. In its applications, the technique is particularly used for the purpose of reducing power consumption and heat losses. In practice, FPGA integrated circuits are used. The voltages of the stator phases are sampled and introduced into the FGPA controller which in turn calculates the switching times. The MLI reference duty cycle is acquired and communicated by an internal resistor and an 8-bit Analogue / Digital converter [1].

#### 3.4.5.6 The technique of controlling hysteresis currents

It uses a MLI strategy in which the usual converter using its switches is reduced to a converter using just four switches and an auxiliary capacitor. The problem in this technique is an asymmetric voltage problem [21].

The consequence on the PWM strategy is that switching is done every 60 degrees. The hysteretic current control technique provides robust torque and speed response compared to voltage control using the MLI strategy. In this configuration the equation $I_c = -(I_A + I_B)$ is still valid.

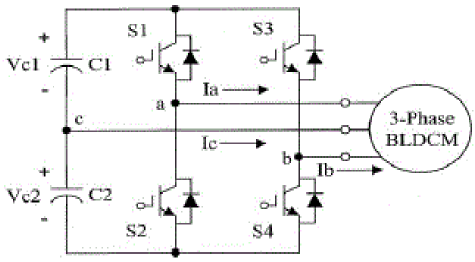



**Figure 3.9** Four-step converter for driving a three-phase BLDC motor

It is interesting to note that this technique, although reduced to the control of two current-conducting phases, allows the system to behave as a system in which control is provided over the three phases and having the ability to behave as a system in which driving phases with a cycle of 120 degrees.

Machine control is actually an approach deduced from the estimates or modelizations that one realizes after having studied the system or the machine to control to be more precise. The different approaches that we put in place aims to lead to a law of control. The power of the control law is directly related to the power of the approach technique used. For instance, an approach based on mathematical modelling will produce an efficient control law depending on whether the equations used to understand the system are accurate or not. The concept of model uncertainty gives us an idea of how the relationship between modelling and approach and the control law are closely related.

Control of BLDC motors is much more effective when control systems are equipped with a feedback control system. Speed control or position control applications require the use of such devices to make control effective, that is, to achieve the goals proposed from the start. The machine modelling approaches bring out the concept of a system state vector that can be used to represent and describe the dynamic behaviour of a system as a function of the evolution of its state variables. In general, it is difficult to know these variables by measurements, which requires the use of a state observer whose role is to provide a system state vector estimate:

This estimate is most often asymptotic and exponential. [these-boulaid.] The control techniques that we will see in the following lines present the control methods that use the notion of system state vector.

### 3.4.6 Extended Kalman Filter (EKF)

As explained in the previous sections, the control techniques used for non-linear systems differ from those used for linear systems. The use of conventional PID controllers shows big limits when it comes to controlling non-linear systems. This is because the behaviour of nonlinear systems is not predictable, and the state of the system can change rapidly when the variables used to model the system vary or the characteristics of the system vary. For instance, a PID regulator will not be able to control a motor whose resistance varies suddenly. The complexity of linear systems including their modelling requires the use of other control methods and the implementation of other types of controllers whose control laws are adaptive ,namely, they take into account the state of the system to control and its possible variation in time, which is the nature of the systems called observing. They give an approximation of the state vector of the system to be controlled. EKF algorithms permits to estimate the state vector of nonlinear systems, which is the case of BLDC motors which are nonlinear systems. The EKF algorithm is an optimal recessive algorithm that takes all measurements into its processing and ultimately provides an estimate of important variables [1].

The EKF algorithm requires to know the dynamics of the system, the state of the important variables when the system is in the initial state, the description of the errors of the system from a statistical point of view. The method using the EKF algorithm is used to estimate the position of the rotor as well as to estimate the speed of the latter. We are not supposed to ignore that the rotor position remains the most important information for determining the switching times in the stator coils of the BLDC motor. This algorithm comes into application to determine the motor state variables after the stator line voltages and currents have been determined. It is necessary that the electrical quantities are not filtered during the treatment. One of the disadvantages of this method is that the algorithm requires a lot of calculations, which requires a well-fitting formulation to get the best of the algorithm.

The advantage is that the position and the speed of the motor are precisely determined whether it is during the steady state or during the dynamic regime. The EKF method easily manages the limits related to the imperfections and non-linearity of the model used and is part of the methods of used in wide applications regarding the sensorless control. The development of high-tech processors alleviates or even eliminates the challenges associated with the tedious calculations required by the EKF algorithm.

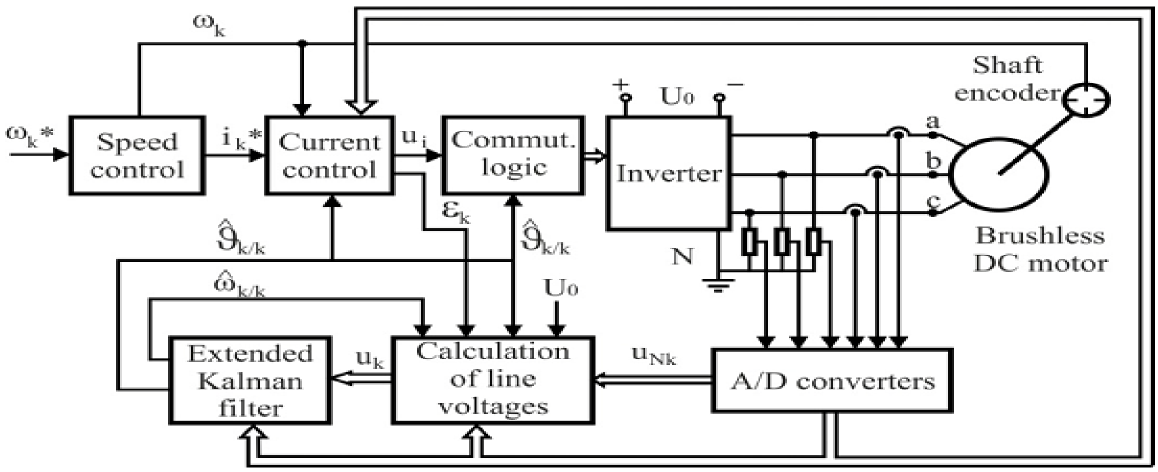



**Figure 3.10** Speed and Position Control Using the Kalman Filters Method

Figure 3.10 the configuration of the speed and position estimation system of a BLDC motor using the EKF method. The entire system can be divided into two parts, one part containing the power circuit and a second part containing the EKF algorithm. It works as follows:

•The first part, which contains the power circuit, consists in switching the current as well as controlling the speed and the current in the motor. It consists of a DC generator, the inverter system and the actuator itself, that is to say the motor and the circuits for controlling these three parts constituting the power circuit.

•The second part containing the EKF algorithm consists of applying a recursive algorithm to determine the system state vector. To do this, a calculator block allows to determine the average of the line voltages in a sampled time $k(u_k)$, which permits to determine the vector line voltages. This tension is calculated considering the voltages at the stator terminals compared to the neutral point vector. In short, this is the potential difference between the neutral point and the stator winding. This potential difference is defined by $U_{Nk}$, the switching of transistors with reference to its duty cycle is defined by $U_o$ , the DC voltage transformed by the inverter is defined by $U_o$, the estimated speed by $w^{k/k}$, the rotor position by $(o^{k/k})$ and the measured current vectors $(ik)$.

One of the peculiarities of non-linear control systems, and what makes them more powerful than linear control systems, is their ability to react according to the features of the system to control and its variations over time.

Advances have been made in the field of control using the EKF method. The use of the stator resistors, the rotor flux and the angular velocity of the rotor simultaneously with a system adapted to the reference model (MRAS) have been realized but the disadvantage of the solution is that it is sensitive to variations rotor and stator resistors. Another method called Bi-input EKF uses the EKF algorithm and the information based on the stator and rotor resistors estimation model. The advantage results in an improved control of the speed, a very precise estimation of the rotor flux, the load torque as well as the angular velocity of the rotor and a non-sensitivity to the variations of the resistors of the stator and the rotor.

### 3.4.7 Sliding -Mode Variable Structure Control

In recent years, the control industry has developed very advanced control systems. As the structures of the controller systems become more complex, the usual control systems such as PID controllers, for example, lose their place. Therefore, we are witnessing the creation of mixed control systems, most often PID controllers coordination with other types of controllers, all this to improve the performance of controllers and to make the control of the control systems not only possible but also effective [25].

The emergence of non-linear systems from a technical point of view has led to the development of control systems for nonlinear systems. Above we have some control systems such as intelligent controllers that appear as a solution to the control of nonlinear systems like BLDC motors.

Fuzzy controllers, neural network controllers and genetic controllers are some of these types of controls that help in controlling BLDC motors.

Beyond these control methods, we have seen the systems observe with Kalman filters. In the same register, there is another control system called variable structure control with sliding mode. It is one of the largest research topics in the field of control motorering. Simulations and experiments have revealed that the variable structure control strategy is more robust than the PID strategy against external disturbances and disruption models [25].

Systems of variable structure act on the system to be controlled by considering the evolution of its state vector. Studies [26] on systems of variable structure, when controlling systems, have shown that the dynamics of the system is not only determined by the feedback controllers used but also by the switching strategy adopted. Starting from the equations of state modelling a system that one seeks to control, and by taking a control law to control the system with different switching strategies, one realizes that the different switching strategies have different influences on the systems to control.

The system can be stable under the application of a switching strategy and not be on the other, even if the control laws adopted remain the same.

Variable structure control is a nonlinear technique for controlling nonlinear systems. This technique offers advantages that cannot be obtained with the use of conventional linear controllers [25]. Slip control is a technique of variable structure control by which a system is forced to behave according to a certain control law. Slip control uses feedback controllers acting on the system to be controlled based on a predetermined area in which the system must evolve. The system to be controlled is represented by a set of points, the feedback controllers influence the representative points of the system so that these points are approaching the predetermined surface. When this is done, the evolution of the system is limited to this surface. This surface is a state space called a sliding surface. The purpose of the slip control is to keep the representative points of the system in the sliding surface or at the boundaries of the sliding surface [34].

The advantages of such a control is that the uncertainties of the mathematical model and the external perturbations do not affect the dynamics of the controlled system, the closed-loop response becomes totally indifferent to the uncertainties related to the system. The fast switching offered by the control to Sliding variable structure provides opportunities for better control over current ripples caused by load variation and switching in windings. [26,27]

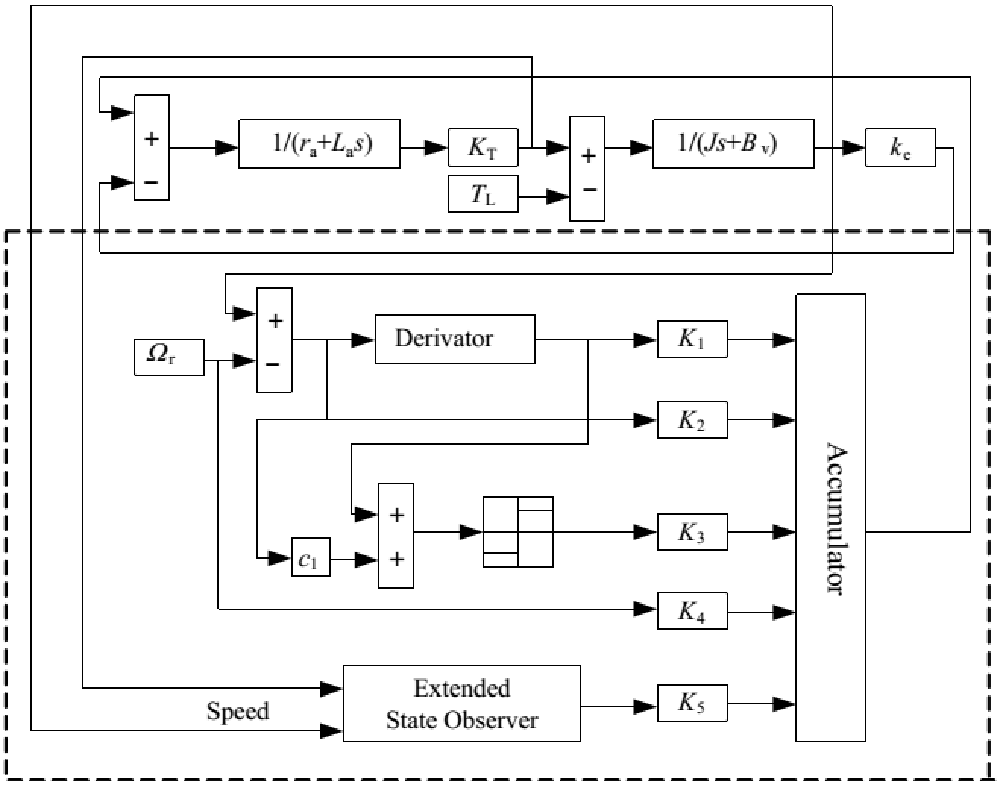



**Figure 3.11** Variable structure control based on an extended state observer.

Figure 3.11 shows a simple closed-loop speed control system using slip control $k_1, k_2, k_3, k_4$ *and* $k_5$ are the parameters of the variable structure control system. This control system is realized starting from the modelling equations of a BLDC motor. The system is a second order system represented by state equations.

$$\begin{cases} \dot{x}_1 = x_2 \\ x_2 = -\dfrac{(r_a J + B_v L_a)}{L_a J} x_2 - \dfrac{(B_v r_a + k_e k_T)}{L_a J} x_1 + \dfrac{K_T}{L_a J} u - \dfrac{r_a T_L}{L_a J} \end{cases}$$

$x_1$ is the angular velocity of the motor, $T_L$ the load of the motor, which is considered as a disturbance which will be estimated by observing it of prolonged state. The experimental results obtained reveal that the variable structure controllers are better than the PID controllers in a BLDC motor speed control. With controllers having variable structure, we obtain less speed ripple, less overshoot, a fast R speed response, indifference despite the variation of the load. At any time, if the state of the system leaves the switching line, the controller changes structure in order to force the system to restart at the switch line. On the other hand, disadvantages arise during very high speed operation. When the motor is operating at high speed, the representative points of the system tend to really exceed the switching line during a certain period. The exceedances are converted into disruption producing undesirable instabilities when the system converges to the original phase plane. By switching the controller structure to a conventional controller structure, this problem is settled.

### 3.5 Conclusion

Since the brushless direct current motors began to attract the attention of people because of their great abilities to produce good torque and less loses during their operation due to the absence of brush in their constitution , many control technics have started to be developed in other make the operation of those electrical motors following certain conditions of torque, speed during various characteristics of operation. This chapter presents those methods and gives another point of view regarding the Sensorless control of BLDC motors.

# CHAPTER 4: APPLICATION OF SENSORLESS SPEED CONTROL OF BLDC MOTOR USING THE SPACE VECTOR PULSE WIDTH MODULATION (SVPWM) CONTROL TECHNIQUE APPLIED TO THE VOLTAGE INVERTER

Motor control is one of the most dynamic branches of dynamic systems motorering. The diversity of electric motors also leads to an increased development of electric motor control methods.

After making a general development of BLDC motors and giving the different methods that are used nowadays to control these motors, in this part we will work on a different way of controlling which is the sensorless control of BLDC motors.

The advantage of practicing a sensorless control is notorious because it increases the reliability of the machine and its ability has evolved in tight places as has been emphasized in previous chapters.

Today, there are very powerful methods for sensorless control of BLDC motors. As such we can mention the sliding mode control which today is increasingly used and studied to allow an efficient control of BLDC motors. The nature of the behavior of BLDC motors which is a nonlinear behavior forced the ingeneer to develop control systems capable of being robust enough to be less dependent on mathematical model equations and thus to compensate for variations of the mathematical model and behaviors non-predictable model related to nonlinear nature.

Beyond the techniques developed and how powerful they are, there are always limits related to the design of the control system because any control system is based on a logic that is never true. Nowadays, we know that when a BLDC motor works, just two phases are powered, the flow of electric current is ensured only by two phases between two commutations and so on. In a BLDC motor a phase and this cyclically is always floating, non-conductive this electric current.

The BLDC motor has the reverse of conventional DC motor has no collector or brushes. Thus, the switching of the electric current in the stator coils is provided by an electronic system whose operating principle is highly dependent on the rotor position. The position of the rotor is essential for determining the switching sequence and which phases must be energized to enable the conduction of the electric current.

The method used today is to start the motor in an open loop by backing up performance, and when the motor has started, the open loop takes control by regulating open loop start errors and the system resumes normal operation.

Open loop control can never be effective because [36] it does not provide feedback on the actual behaviour of the motor. In fact, the output quantities such as speed, torque or output currents are not known. This impossibility of knowing these magnitudes makes it impossible to determine the real behaviour of the motor. Space vector width modulation control technique is a powerful control method because it uses a closed loop and in addition to that it tracks the rotor angle by a programmable language. The control is realized without the use of any physical sensor but by the introduction of code which permit to force the motor react in a desired way.

The schematic bloc of the system that we will apply is as follow.

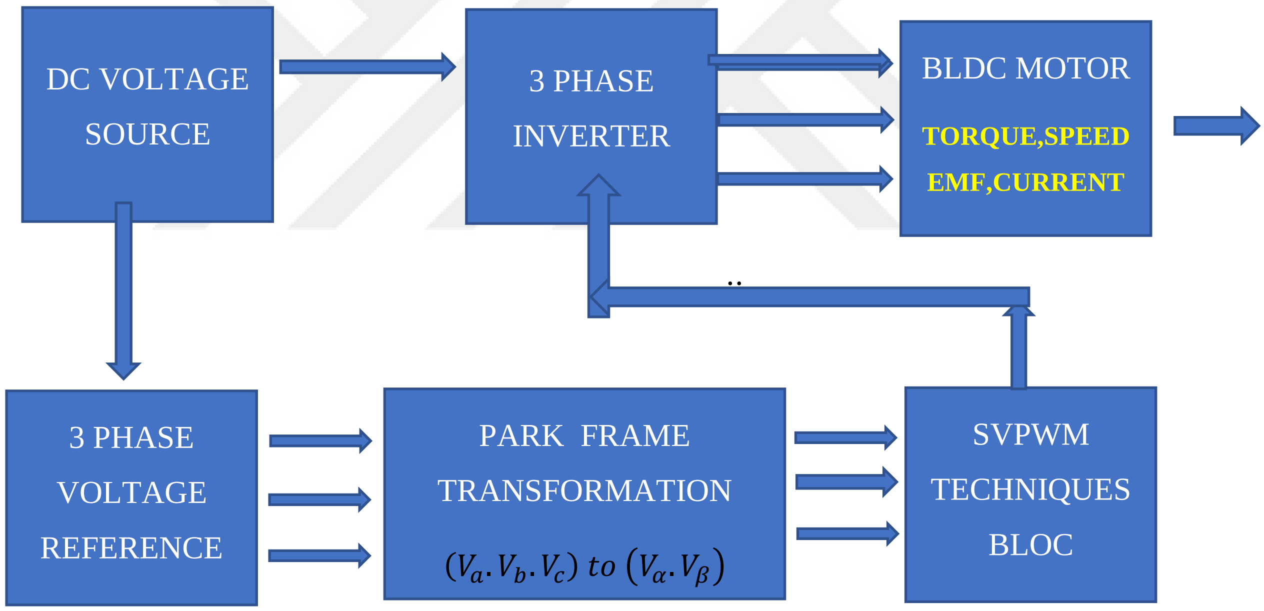



**Figure 4.1** Drive system block diagram

Practically, the major part of the system is one DC bus which give a constant voltage, one inverter system which is controlled by the SVPWM technique bloc after alternative voltage coming from the park transformation frame have been processed. The simulation uses a programmable code on MATLAB for the Park transformation and the space vector width modulation.

In the lines that follow, we will proceed to the modeling of the different parts of the control system

## 4.1 Modeling of the Motor

We will therefore perform electrical modeling, which refers to the electrical equations of the machine which are actually a generalization of Ohm's law and mechanical modeling, which refers to Newton's second law.

BLDC motor operating by delivering current to its stator in reference to the rotor through inverter. The flux generated by the stator, the current magnet with which the permanent magnet rotor flows which develops torque. The rotor rotates in a specific direction to align with the stator flow at synchronous speed. The stator is effectively switched to an unidirectional rotation.

- **Hypothesis**

We will retain the following hypotheses:

- The machine is three-phase and balanced
- The windings of the motor are connected in star
- The magnetic material is not saturated
- The permeability of iron is supposed to be infinite
- The detent torque of the machine is considered as zero.

We also consider that the permeability of magnets is close to that of air, that it is equal to 1. The machine contains smooth poles. The inductor is of low value and does not vary. The air gap being wide, it is considered that the fluxes induced in the stator are small compared to the fluxes induced by the magnets of the rotor [33]. The armature reaction is negligible. It is considered that the values of the resistances do not vary. They are therefore considered to be constant. The operating point of the machine has no influence on the flow distribution. The modelling of the BLDC motor is like the DC motor.

BLDCM modelling consists of two parts:

An electrical part and a mechanical part.

Electrical modelling is based on the ohm law. By applying a mesh law in the electrical circuit representative of an electrical phase, it is possible to determine the electric model of the machine.

First by taking each phase individually, the following equations model the state of the motor electrically.

$$v_a = Ri_a + (L - M)\frac{d}{dt}i_a + e_a \quad (E\ 4.1)$$

$$v_b = Ri_b + (L - M)\frac{d}{dt}i_b + e_b \quad (E\ 4.2)$$

$$v_c = Ri_c + (L - M)\frac{d}{dt}i_c + e_c \quad (E\ 4.3)$$

Where $V_a, V_b, V_c$ are the phase voltages, $i_a, i_b\ and\ i_c$ represent the phase currents and $e_a, e_b, e_c$ are the electromotive forces of the different phases a, b and c. L is the inductance of each motor phases.

The electrical model of the 3 phases can therefore be described by the following equations:

$$v_{ab} = R(i_a - i_b) + L\frac{d}{dt}(i_a - i_b) + e_a - e_b \ (E\ 4.4)$$

$$v_{bc} = R(i_b - i_c) + L\frac{d}{dt}(i_b - i_c) + e_b - e_c \ (\ E\ 4.5)$$

$$v_{ca} = R(i_c - i_a) + L\frac{d}{dt}(i_c - i_a) + e_c - e_a \ (\ E\ 4.6)$$

The relation between the torque and the motor speed is given by :

$$T_e = k_f w_m + J\frac{dw_m}{dt} + T_L \ (E\ 4.7)$$

The notations $v_{ab}, v_{bc}, v_{ca}\ and\ i_a,\ i_b, i_c\ and\ e_a, e_b\ et\ e_c$ represent respectively the phase to phase voltage magnitude, the current and the electromotive force between phase a,phase b and phase c.

The motion equation is given by : $\frac{dw_m}{dt} = \left(\frac{1}{J}\right)\left(T_e - T_L - \frac{k_f 2w_e}{P}\right)$ avec $w_e = \frac{P}{2}w_m\ (E\ 4.8)$

P is the poles number of the motor, $T_e$ represents the electromagnetic torque and $T_L$ is the load torque. $J$ is the rotor inertia, $k_f$ the friction constant et $w_m$ represents mechanical rotor speed.

$e_a = \frac{k_e}{2}w_m F(\theta_e)\ ;\ e_b = \frac{k_e}{2}w_m F(\theta_e - \frac{2\pi}{3})\ \ e_c = \frac{k_e}{2}w_m F(\theta_e - \frac{4\pi}{3})\ ;\ (E\ 4.9)$

Knowing that the electromagnetic power $P_t = e_a i_a + e_b i_b + e_c i_c\ (E\ 4.10)$ alors

$$T_e = \frac{P_e}{w_m} \Leftrightarrow \frac{e_a i_a + e_b i_b + e_c i_c}{w_m} \ (E\ 4.10)$$

$$\Leftrightarrow \frac{1}{w_m}(\frac{k_e}{2}w_m F(\theta_e)i_a + \frac{k_e}{2}w_m F\left(\theta_e - \frac{2\pi}{3}\right)i_b + \frac{k_e}{2}w_m F(\theta_e - \frac{4\pi}{3})i_c\ )$$

$$T_e = \frac{k_t}{2}\left[F(\theta_e)i_a + F\left(\theta_e - \frac{2\pi}{3}\right)i_b + F(\theta_e - \frac{4\pi}{3})i_c\right]\ (E\ 4.11)$$

$k_e$ $fem$ constant et $k_t$ represents the electromagnetic torque constant. $\theta_e = \theta_m \frac{P}{2}$.

$F$ function gives the trapezoidal wave form of the electromotive force. One period of $F$ can be writen like:

$$F(\theta_e) = \begin{cases} 1, & 0 \le \theta_e < \frac{2\pi}{3} \\ 1 - \frac{6}{\pi}\left(\theta_e - \frac{2\pi}{3}\right), & \frac{2\pi}{3} \le \theta_e < \pi \\ -1, & \pi \le \theta_e < \frac{5\pi}{3} \\ -1 + \frac{6}{\pi}\left(\theta_e - \frac{5\pi}{3}\right), & \frac{5\pi}{3} \le \theta_e < 2\pi \end{cases} \quad (E\ 4.12)$$

In order to be able to represent the equations for the simulations, it is necessary to use the spatial state representation.

Thus, it is necessary to eliminate one of the phases in the representation of the tensions.

$$\text{Given } i_a + i_b + i_c = 0 \Leftrightarrow i_c = -(i_a + i_b) \quad (E\ 4.13)$$

$$v_{ab} = R(i_a - i_b) + L\frac{d}{dt}(i_a - i_b) + e_a - e_b\ (E\ 4.14)$$

$$v_{bc} = R(i_b - i_c) + L\frac{d}{dt}(i_b - i_c) + e_b - e_c\ \ (E\ 4.15)$$

$$v_{bc} = R(i_b + i_a + i_b) + L\frac{d}{dt}(i_b + i_a + i_b) + e_b - e_c$$

$$v_{bc} = R(i_a + 2i_b) + L\frac{d}{dt}(i_a + 2i_b) + e_b - e_c\ \ (E\ 4.16)$$

Then we have :

$$\begin{pmatrix} i_a \\ i_b \\ w_m \\ \theta_m \end{pmatrix} = \begin{pmatrix} -\frac{R}{2} & 0 & 0 & 0 \\ 0 & -\frac{R}{2} & 0 & 0 \\ 0 & 0 & -\frac{k}{f} & 0 \\ 0 & 0 & 1 & 0 \end{pmatrix} \begin{pmatrix} i_a \\ i_b \\ w_m \\ \theta_m \end{pmatrix} + \begin{pmatrix} \frac{2}{3L} & 0 \\ -\frac{1}{3L} & 0 \\ 0 & \frac{1}{3} \\ 0 & 0 \end{pmatrix} \begin{pmatrix} v_{ab} - e_{ab} \\ v_{bc} - e_{bc} \\ T_e - T_L \end{pmatrix}$$

$$\begin{pmatrix} i_a \\ i_b \\ w_m \\ \theta_m \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ -1 & -1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} i_a \\ i_b \\ w_m \\ \theta_m \end{pmatrix} \quad (E\ 4.17)$$

**4.2 Inverter modelling and control**

Inverters have become very important today in the power supply of industrial machines. An inverter is defined as a converter of power electronics whose purpose is to convert a continuous energy into an alternative energy.

The advantage of using inverters lies in the fact that with an inverter it is possible to supply an AC circuit at any frequency with sinusoidal characteristics which may be completely different from the voltages and currents provided by the networks. from power plants.

The inverters are composed of electrical switches which can be IGBT, MOS or GTO transistors provided with a diode in parallel according to the power to be transmitted.

Motor control today can not be done without the help of inverters. The fact is that there is a multitude of rotating machines and they are not all powered by currents whose waveform is the same. The design of asynchronous motors used for the usual applications does not require the use of inverters because it is made so that the waveform of the feed currents of the machines is compatible with the waveform of the currents generated by the inverters. power plants and these motors run at constant speed. Particular motors such as BLDCs do not use sinusoidal three-phase voltages like asynchronous motors, and since it is impossible to have usual voltage sources generating voltages of these waveforms, it is therefore necessary to use voltage inverters. In addition, variable speed drive applications require the use of inverters. The figure shows an example of an inverter supplying an motor.

The particularity of these inverters is that they do not operate autonomously, It requires a control law to meet the requirements of BLDC motors. There are several methods to control the inverters. One of these methods and the most effective is the PWM command. The MLI makes it possible to simply and efficiently create the waveform to be applied to the machine. In the figure, the states of the switches are imposed by the MLI. The control logic takes into account the fact that the two switches of the same arm can not drive at the same time, so they ordered in a complementary way. When one switch drives the other must not drive and is therefore controlled. So driving switches are never on the same arm.

$$S_i = (i = a, b, c) \qquad (E\ 4.18)$$

If $S_i = 1$ then the top switch is closed and the bottom switch is open.

If $S_i = 0$ , then the top switch is open and the bottom switch is closed

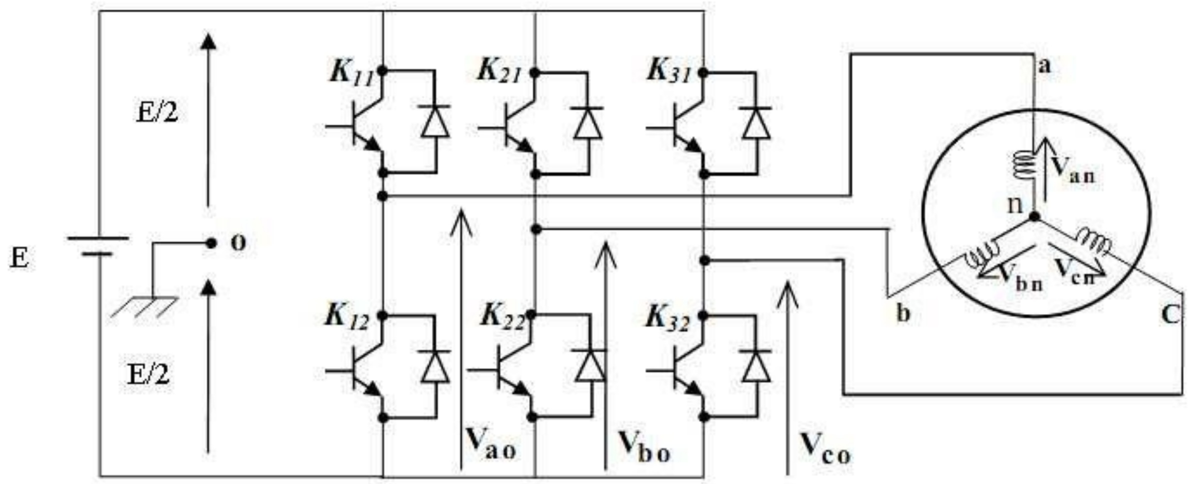



**Figure 4.2** Two-level voltage inverter

Thus during the modeling of the inverter, it is also necessary to model the control law, which passes by the choice of the MLI method that will be applied to the inverter to achieve the desired goal but also to use the inverter efficiently by minimizing losses.

In our work, we will use a two-level UPS. Multilevel inverters can increase the output voltage of static converters beyond semiconductor boundaries. Most often, to achieve them, there are several sources of DC voltage. In this kind of machine, the output voltage can have several levels.

The multilevel inverters are used in high power applications and in variable speed drives in which the speed of rotation is very high and is most often greater than 5000 rpm.

It is important to be able to know the voltages by phase compared to the value of the cyclic ratios. Thus, it is necessary to consider certain states that will allow better evaluation.

- First, it is assumed that the motor is star-coupled and that the currents flowing in its windings are equal in standards

- The switches are perfect, so there is no voltage drop or loss of power

- The sum of the stator currents is zero and the neutral of the motor is not connected to the midpoint of the inverter.

- To avoid complicating the system, all output voltages have the same reference point

- The DC voltage source supplying the inverter is ideal.

Under these conditions, the phase voltages can be expressed as a function of the control logic $S_i$ .

$$U_{in} = S_i U_c - \frac{U_c}{2} \quad \text{(E 4.19)}$$

Moreover, starting from the point O of the source, one can express phase to phase voltages $V_{ab}, V_{bc}, V_{ca}$ .

$$\begin{cases} V_{ab} = V_{ao} + V_{ob} = V_{ao} - V_{bo} \\ V_{bc} = V_{bo} + V_{oc} = V_{bo} - V_{co} \\ V_{ca} = V_{co} + V_{oa} = V_{co} - V_{ao} \end{cases} \quad \text{(E 4.20)}$$

Applying Chasles's relation to input voltages $V_{ao},\ V_{bo}\ et\ \ V_{co}$ , on a :

$$\begin{cases} V_{ao} = V_{an} + V_{no} \\ V_{bo} = V_{bn} + V_{no} \\ V_{co} = V_{cn} + V_{no} \end{cases} \quad \text{(E 4.21)}$$

As mentioned above, the system is voltage balanced, so from the neutral point of the motor, we have the following relationship:

$$V_{an} + V_{bn} + V_{cn} = 0 \quad \text{(E 4.22)}$$

Adding the volages, we have: $V_{ao} + V_{bo} + V_{co} = 3V_{no}$ and consequently,

$$V_{no} = \frac{1}{3}(V_{ao} + V_{bo} + V_{co}) \quad \text{(E 4.23)}$$

By replacing (5) in (3), we get:

$$\begin{cases} V_{an} = \frac{2}{3}V_{ao} - \frac{1}{3}V_{bo} - \frac{1}{3}V_{co} \\ V_{bn} = -\frac{1}{3}V_{ao} + \frac{2}{3}V_{bo} - \frac{1}{3}V_{co} \\ V_{cn} = -\frac{1}{3}V_{ao} - \frac{1}{3}V_{bo} + \frac{2}{3}V_{co} \end{cases} \quad (E\ 4.24)$$

By using the expression (1), we can write that:

$$\begin{bmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{bmatrix} = \frac{U_c}{3} \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \begin{bmatrix} S_a \\ S_b \\ S_c \end{bmatrix} \quad \text{(E 4.25)}$$

Taking $i = \{a, b, c\}$ , $V_{in}$ represents the output voltages et $V_{io}$ the input voltages.

We can say that $[V_{in}] = [T][V_{io}]$ with :

$$[T] = \frac{1}{3} \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \quad (E\ 4.26)$$

The control of the inverter will be ensured by a modulation structure of the pulse width which is abbreviated by PWM. Pulse width modulation is now one of the most powerful and widely used methods in motor control. It makes it possible to vary the speed of the motors with a high efficiency. [32]

There are several types of MLI, and each type of MLI has its well-defined characteristics. The choice of a technique depends on the type of machine to be controlled, the power range, the semiconductors used for the inverter and the simplicity of implementation of the algorithm. It is ultimately cost and performance criteria that will determine this choice. The performance criteria make it possible to evaluate and compare the qualities of the different MLI techniques.

The modulation of the intersective pulse width or triangle sine operates according to the following principle: First, one has a sinusoidal reference or another form having a frequency $f_s$, this reference is called the modulator. Second, we have a triangular signal called the frequency carrier $f_p$. This signal is characterized by a high frequency.

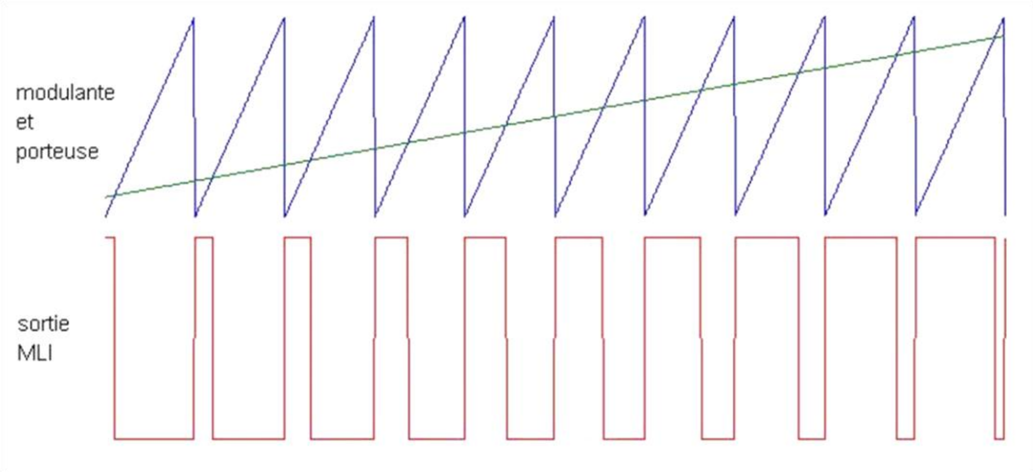



**Figure 4.3** Modulation of the intersective pulse width

By using the points of intersection of the two references, the switching times of the switches of the inverter are determined. Generally, the carrier is triangular. The output signal of the MLI is 1 if the modulator is larger than the carrier and it is 0 otherwise. Thus we can also notice that the output signal changes state at each intersection of the modulator and the carrier.

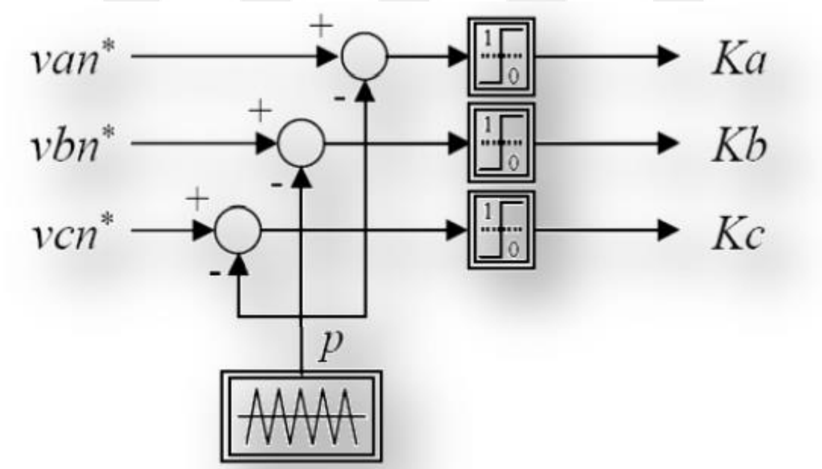
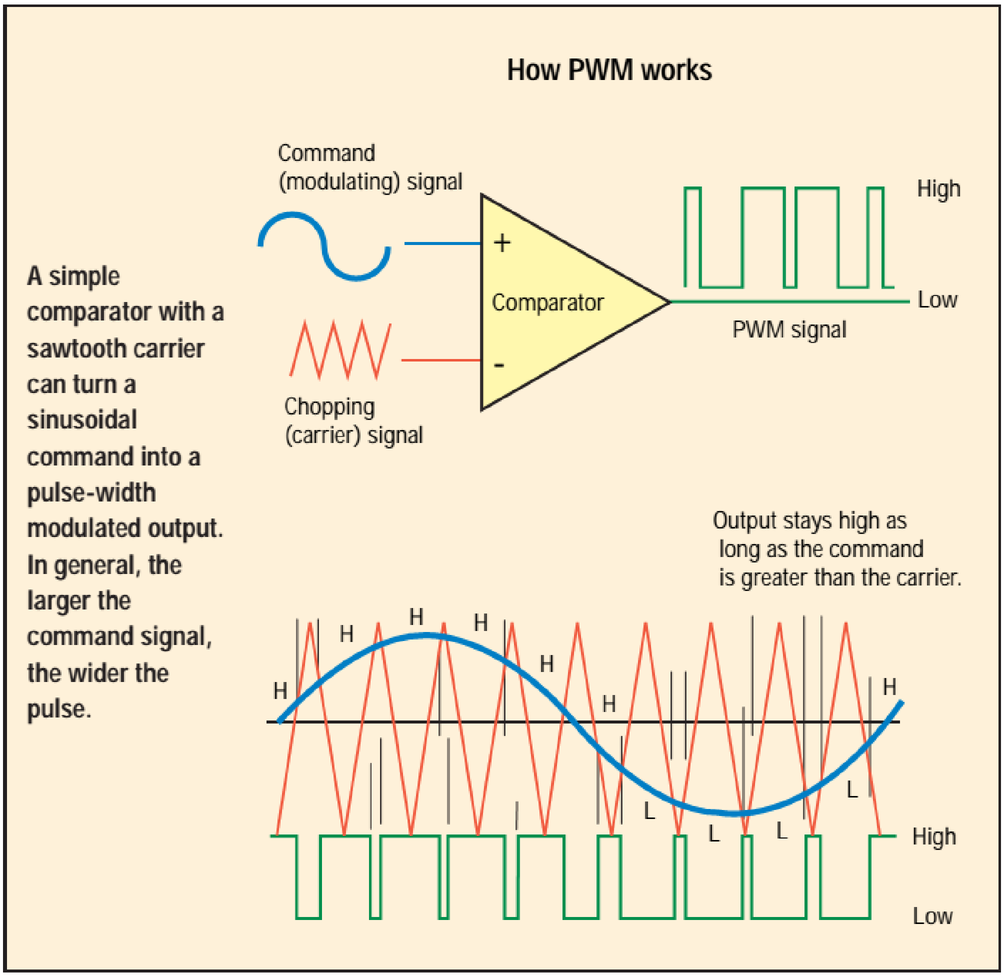
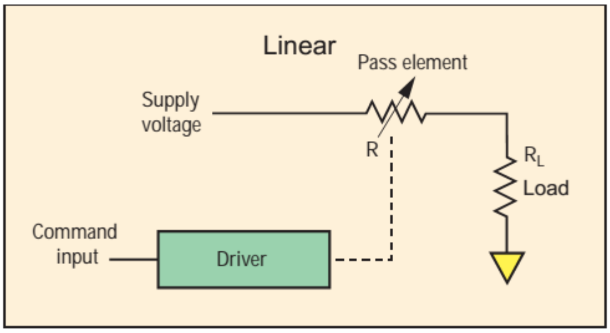



**Figure 4.4** Outline Diagram of the Intersecting MLI

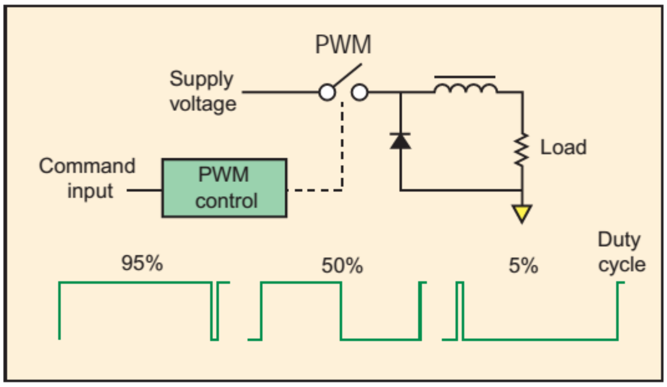
The downside of this command is that it limits the performance of the motor because the maximum value of the voltage can only reach half the dc voltage applied to the inverter. This technique is used in applications in which high power transfer is not high.

The diagrams in the following figure show how the PWM command works and how a PWM structure appears much more efficient and effective than a control structure using voltage drives for control. Indeed, control using MLI is a pulse control. The lengths of the periods are directly proportional to the speed of the motor.




Linear amplifiers vary the resistance of a pass element to regulate power. Efficiency is fine at the extremes — losses are minimal when $R = 0$ or $\infty$ — but suffers elsewhere, bottoming out at midrange ($R = R_L$) where the amount of energy wasted as heat in the amplifier equals that delivered to the load.




The output of a PWM amplifier is either zero or tied to the supply voltage, holding losses to a minimum. As the duty cycle changes to deliver more or less power, efficiency remains essentially constant.

**Figure 4.5** System working with MLI and normally

Our inverter system as we said above will be controlled by a MLI structure because this control seems most effective compared to the types of controls whose purpose is to directly vary the voltage across the motor.

As we know, an inverter has the essential purpose of transforming a DC voltage into an AC voltage. The structure of the inverter components of the power electronics so-called switch. Closing and opening these switches will therefore create an output voltage of a certain wave form. The control of the switches is carried out by the technique of the modulation of the pulse width .

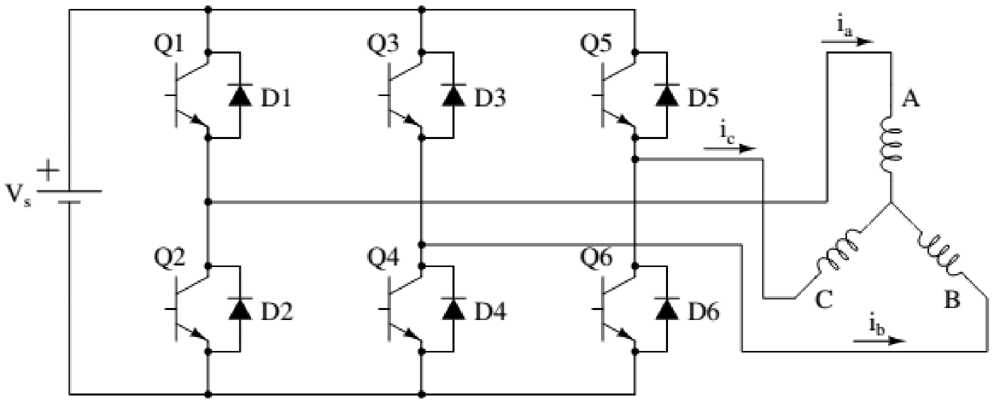



**Figure 4.6** Simplified diagram of a BLDC motor control system

A BLDC motor is a three-phase machine whose optimal operation is conditioned by the simultaneous supply of two phases of the motor during an interval of 60 degrees of time. The non-powered phase carries the necessary information for switching in the stator coils. The studies show that the switching time is determined by three important events: the DC source voltage, the rotor position and the value of the electromotive force and the state of the current conducting phases, ie say whether the current in these phases is zero or not. Figure 5 shows the BLDC motor and the inverter for power supply. This diagram can be reduced to a much simpler diagram during the various phases of operation of the machine. Depending on the phases leading the electrical energy, we model the system so that we find ourselves with a diagram perfectly reflecting the actual state of the machine as to its active operation. Thus one will model the system according to conduction intervals all corresponding to 60 electrical degrees. In addition, for the optimal operation of the motor, there is a sequence of operation of the electronic switches. This sequence is shown in Figure 6 below.

| Switching interval | Seq. number | Pos. sensors | | | Switch closed | | Phase Current | | |
|---|---|---|---|---|---|---|---|---|---|
| | | H1 | H2 | H3 | | | A | B | C |
| $0° - 60°$ | 0 | 1 | 0 | 0 | Q1 | Q4 | + | - | off |
| $60° - 120°$ | 1 | 1 | 1 | 0 | Q1 | Q6 | + | off | - |
| $120° - 180°$ | 2 | 0 | 1 | 0 | Q3 | Q6 | off | + | - |
| $180° - 240°$ | 3 | 0 | 1 | 1 | Q3 | Q2 | - | + | off |
| $240° - 300°$ | 4 | 0 | 0 | 1 | Q5 | Q2 | - | off | + |
| $300° - 360°$ | 5 | 1 | 0 | 1 | Q5 | Q4 | off | - | + |

**Figure 4.7** Sequence of operation

The modeling of each operating interval is shown in Figure 7. Free-wheeling diodes are used for phases that stop driving. In other words, the phases of the motor are found in a cyclic game in which when the switching is engaged, the conductive phase stops driving and the non-conductive phase begins to conduct the electric current. The current of the conductive phase will therefore decrease from nominal value to zero. This process takes place through a freewheeling diode. On the other hand, the phase that begins to drive electric sees its current go from zero to reach a nominal operating value.

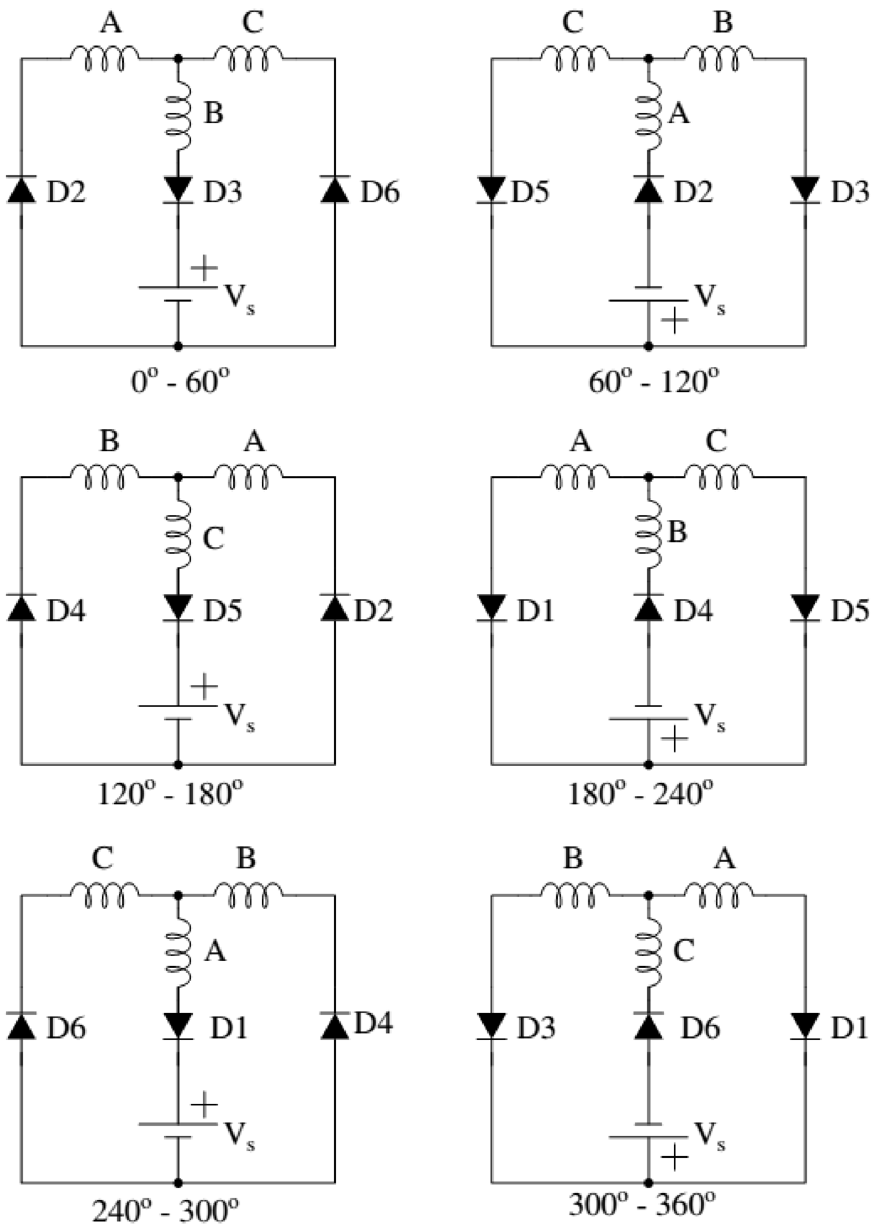



**Figure 4.8** Configuration of the different circuits during each conduction period

When the current in the freewheeling diode is not zero, the phase-to-phase voltage is such that:

$$v_{ab} = v_s, v_{bc} = 0 \; and \; v_{ca} = -V_s \quad (E\ 4.27)$$

When the current is zero, the value of the voltages $v_{bc}$ et $v_{ca}$ is different and depends on the value of the electromotive force.

It is possible to obtain the topology of the circuit, which makes it possible to recreate two circuits in which the voltage sources are oriented differently. In the first voltage source, the voltage is positive and in the second voltage source the voltage is negative. This topology accounts for the operating states of the circuit. In addition, the phases of the motor are represented by the numbers 1,2 and 3. The electromotive forces of the different phases by the sources voltages $e_1, e_2$ et $e_3$. The diodes have voltage drops at their terminals, thus the source of voltage $v_{d3}$ behaves like a freewheel diode. Voltages $v_{bc}$ et $v_{ca}$ must always be known because the modeling of the motor requires two voltages.

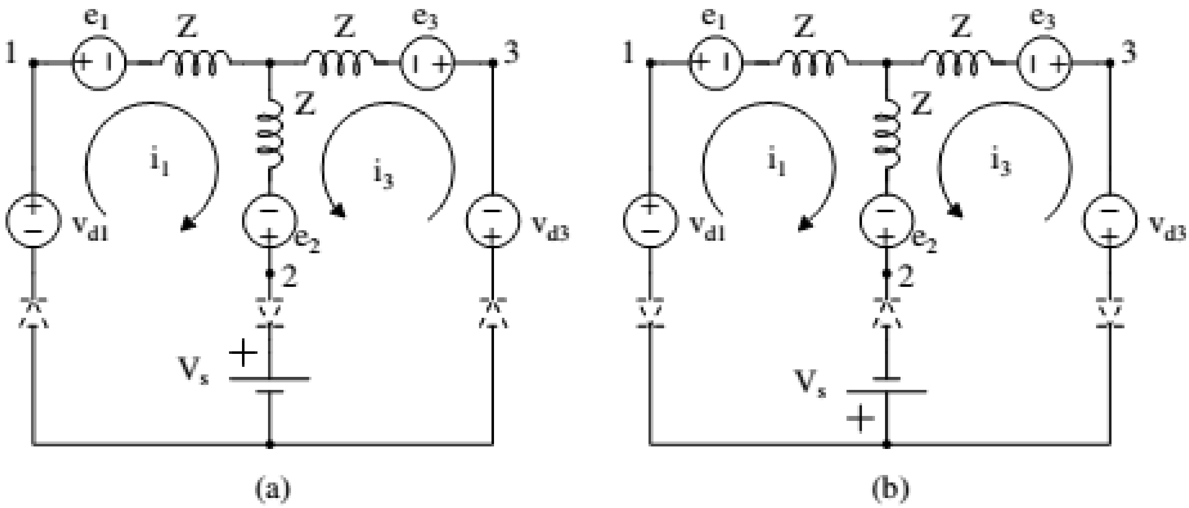



**Figure 4.9** Topology of the circuit

The inverter system also considers the state of the freewheeling diode. In other words he is reassured that the current through the freewheeling diode only flows in one direction. Thus when the current is not zero in the diode, the voltage of $v_{d3}$ is equal to zero. When the current is zero, the diode must produce a voltage that ensures that the current remains at zero in this phase until the conduction sequence responsible for the conduction of this phase arrives so that it can start drive again. The value of this voltage can be easily determined by a calculation in which it is assumed that the current $i_3$ *is a function of voltage sources and by posing* $i_3 = 0$, we get:

For the circuit 8.a, we have :

$$i_3 \neq 0 \; gives \begin{cases} v_{12} = V_s \\ v_{23} = 0 \\ v_{31} = -V_s \end{cases} \; et \; i_3 = 0 \; gives \begin{cases} v_{12} = V_s \\ v_{23} = \dfrac{1}{2}(-V_s + e_1 + e_2 - 2e_3) \\ v_{31} = \dfrac{1}{2}(-V_s - e_1 - e_2 + 2e_3) \end{cases} \quad (E\ 4.28)$$

For the circuit 8.b, we have :

$$i_3 \neq 0 \; gives \begin{cases} v_{12} = -V_s \\ v_{23} = 0 \\ v_{31} = V_s \end{cases} \; et \; i_3 = 0 \; gives \begin{cases} v_{12} = -V_s \\ v_{23} = \frac{1}{2}(V_s + e_1 + e_2 - 2e_3) \\ v_{31} = \frac{1}{2}(V_s - e_1 - e_2 + 2e_3) \end{cases} \quad (E\ 4.29)$$

In order to allow efficient operation of the inverter, we reduce some data that would make the calculations tedious. Knowing that the voltages between phases must be provided by the inverter, the zero current flows in the diodes and the value of the three electromotive forces against must be known by the inverter. The input voltages of the motor model are the differences between the phase voltages and the electromotive forces between corresponding phases.

Thus, the inverter is designed so that it can only calculate and provide the current phase voltages. We then obtain inverter outputs of this kind:

For the circuit 8.a

$$i_3 \neq 0 \; gives \begin{cases} u_{12} = v_{12} - (e_1 - e_2) = V_s - e_1 - e_2 \\ u_{23} = v_{23} - (e_2 - e_3) = -e_2 + e_3 \\ u_{31} = v_{31} - (e_3 - e_1) = -V_s - e_3 + e_1 \end{cases} \quad (E\ 4.30)$$

$$i_3 = 0 \; gives \begin{cases} u_{12} = v_{12} - (e_1 - e_2) = V_s - e_1 + e_2 \\ u_{23} = v_{23} - (e_2 - e_3) = \frac{1}{2}(-V_s + e_1 - e_2) \\ u_{31} = v_{31} - (e_3 - e_1) = \frac{1}{2}(-V_s + e_1 - e_2) \end{cases} \quad (E\ 4.31)$$

For the circuit 8.b

$$i_3 \neq 0 \; gives \begin{cases} u_{12} = v_{12} - (e_1 - e_2) = -V_s - e_1 + e_2 \\ u_{23} = v_{23} - (e_2 - e_3) = -e_2 + e_3 \\ u_{31} = v_{31} - (e_3 - e_1) = V_s - e_3 + e_1 \end{cases} \quad (E\ 4.32)$$

$$i_3 = 0 \; gives \begin{cases} u_{12} = v_{12} - (e_1 - e_2) = -V_s - e_1 + e_2 \\ u_{23} = v_{23} - (e_2 - e_3) = \frac{1}{2}(V_s + e_1 - e_2) \\ u_{31} = v_{31} - (e_3 - e_1) = \frac{1}{2}(-V_s + e_1 - e_2) \end{cases} \quad (\text{E } 4.33)$$

With this configuration, the inverter provides just two voltages. However, it is still necessary to know the equations of the three voltages for the derivation of the voltages a, b and c. After replacing the numbers 1,2 and 3 respectively by a, b and c, the table below represents the voltage voltages at the output of the inverter, the voltages that are injected at the motor terminals. It is here for the input voltages of the motor.

| El. Angle | Diode Current | $v_{ab} - e_{ab}$ | $v_{bc} - e_{bc}$ |
|---|---|---|---|
| $0° - 60°$ | $i_a \neq 0, i_c \neq 0$ | $-V_s - e_a + e_b$ | $V_s - e_b + e_c$ |
| | $i_a \neq 0, i_c = 0$ | $-V_s - e_a + e_b$ | $\frac{1}{2}(V_s + e_a - e_b)$ |
| | $i_a = 0, i_c \neq 0$ | $\frac{1}{2}(-V_s + e_b - e_c)$ | $V_s - e_b + e_c$ |
| | $i_a = 0, i_c = 0$ | $0$ | $0$ |
| $60° - 120°$ | $i_c \neq 0, i_b \neq 0$ | $-V_s - e_a + e_b$ | $-e_b + e_c$ |
| | $i_c \neq 0, i_b = 0$ | $\frac{1}{2}(-V_s - e_a + e_c)$ | $\frac{1}{2}(-V_s - e_a + e_c)$ |
| | $i_c = 0, i_b \neq 0$ | $-V_s - e_a + e_b$ | $\frac{1}{2}(V_s + e_a - e_b)$ |
| | $i_c = 0, i_b = 0$ | $0$ | $0$ |
| $120° - 180°$ | $i_b \neq 0, i_a \neq 0$ | $-e_a + e_b$ | $-V_s - e_b + e_c$ |
| | $i_b \neq 0, i_a = 0$ | $\frac{1}{2}(V_s + e_b - e_c)$ | $-V_s - e_b + e_c$ |
| | $i_b = 0, i_a \neq 0$ | $\frac{1}{2}(-V_s - e_a + e_c)$ | $\frac{1}{2}(-V_s - e_a + e_c)$ |
| | $i_b = 0, i_a = 0$ | $0$ | $0$ |
| $180° - 240°$ | $i_a \neq 0, i_c \neq 0$ | $V_s - e_a + e_b$ | $-V_s - e_b + e_c$ |
| | $i_a \neq 0, i_c = 0$ | $V_s - e_a + e_b$ | $\frac{1}{2}(-V_s + e_a - e_b)$ |
| | $i_a = 0, i_c \neq 0$ | $\frac{1}{2}(V_s - e_b + e_c)$ | $-V_s - e_b + e_c$ |
| | $i_a = 0, i_c = 0$ | $0$ | $0$ |
| $240° - 300°$ | $i_c \neq 0, i_b \neq 0$ | $V_s - e_a + e_b$ | $-e_b + e_c$ |
| | $i_c \neq 0, i_b = 0$ | $\frac{1}{2}(V_s - e_a + e_c)$ | $\frac{1}{2}(V_s - e_a + e_c)$ |
| | $i_c = 0, i_b \neq 0$ | $V_s - e_a + e_b$ | $\frac{1}{2}(-V_s + e_a - e_b)$ |
| | $i_c = 0, i_b = 0$ | $0$ | $0$ |
| $300° - 360°$ | $i_b \neq 0, i_a \neq 0$ | $-e_a + e_b$ | $V_s - e_b + e_c$ |
| | $i_b \neq 0, i_a = 0$ | $\frac{1}{2}(-V_s + e_b - e_c)$ | $V_s - e_b + e_c$ |
| | $i_b = 0, i_a \neq 0$ | $\frac{1}{2}(V_s - e_a + e_c)$ | $\frac{1}{2}(V_s - e_a + e_c)$ |
| | $i_b = 0, i_a = 0$ | $0$ | $0$ |

**Figure 4.10** Phase voltage during intervals

### 4.3 Space Vector Pulse Width Modulation Calculation

This work will use the SVPWM technique which is part of the best inverter control techniques. Realizing a sensorless control, this technique will allow us to reach our objectives. The SVPWM works in such a way: it receives the information of the rotor's speed through the angle of rotation. Knowing that speed is the derivative of the angular position, it is very easy to be able to determine it. The SVPWM technique is such that after receiving the rotor angle, the system generates two voltages $V_\alpha$ $and$ $V_\beta$. These two voltages are then used to determine the value of the reference voltage vector $V_{ref}$ and the angle α between the voltage vectors. The implementation of the SVPWM technique requires three major steps that are:

- Calculation of $V_\alpha, V_\beta$ $and$ $\alpha$
- Calculation of $T_0, T_1$ $and$ $T_2$
- Determination of all the commutation time of all the switcher devices from $S_1$ $to$ $S_7$

❖ **Calculation of $V_\alpha, V_\beta$ and $\alpha$**

The reference voltage called $V_{ref}$ is given by the following formula. That reference voltage is important because it gives the ability to operate SVPWM technique by determining $V_\alpha, V_\beta$ $and$ $\alpha$ .

$$\left|V_{ref}\right| = \sqrt{V_\alpha^2 + V_\beta^2} \qquad (E\ 4.34)$$

$$\alpha = \tan^{-1}\frac{V_\beta}{V_\alpha} \quad (E\ 4.35)$$

Starting from the relation established above to determine the matrix relation between the simple voltages and the switches, one deduces the relation between the composed voltages and the switches, thus

$$\begin{bmatrix} V_{ab} \\ V_{bc} \\ V_{ca} \end{bmatrix} = U_c \begin{bmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \\ -1 & 0 & 1 \end{bmatrix} \begin{bmatrix} S_a \\ S_b \\ S_c \end{bmatrix} \ (E\ 4.36)$$

The inverter system contains three arms each supporting two switches that are seen as variables. Each of these variables can be seen as a non-zero vector. Six vectors corresponding to the different states of the switches are thus determined, and two vectors which represent the zero state in order to be able to operate the system without problems. In the previous paragraphs, we have explained the operation of each of these switches. By analyzing the different states of these switches, the spatial vectors, which are eight in number, are determined. $(V_0, V_1, V_2, V_3, V_4, V_5, V_6, V_7)$ as we can see in the following pictures.

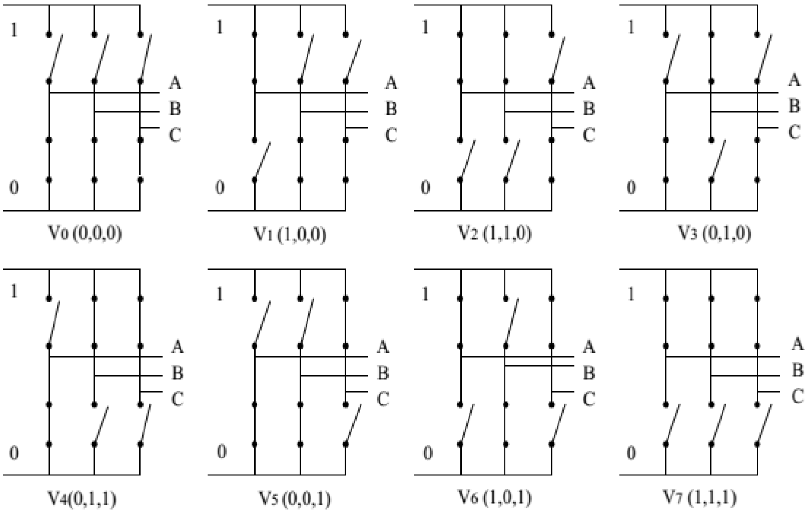



**Figure 4.11** Eight states for the voltage inverter

The output voltages of the inverter are thus divided into six dials forming a hexagon as a trigonometric circle.

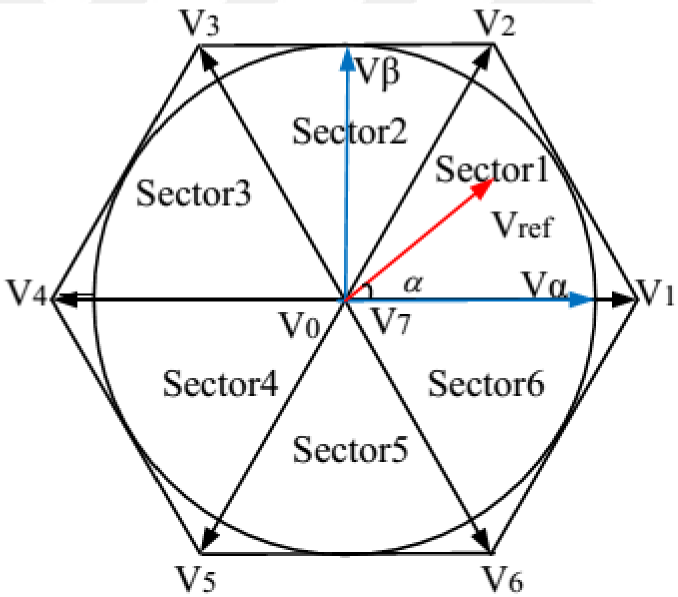



**Figure 4.12** Representation of the different sectors

FIG 4.13 represents the values of the voltages between phases and the voltages between phase and neutral as a function of the different states of the voltage vectors of the inverter. Clark's transformation allows us to establish an essential relationship between the tensions $(V_\alpha, V_\beta)$ and the voltages $(V_a, V_b, V_c)$. It should be noted that the SVPWM techniques receives the voltages $(V_a, V_b, V_c)$ spaced 120 degrees apart from one another and converts them into a two-tension system $(V_\alpha, V_\beta)$ spaced 90 degrees apart from each other.

Then,

$$\begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} = \frac{2}{3}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \quad (E\ 4.37)$$

| Voltage vectors | Switching vectors | | | Line to neutral voltage | | | Line to line voltage | | |
|---|---|---|---|---|---|---|---|---|---|
| | $S_1$ | $S_3$ | $S_5$ | $V_{an}$ | $V_{bn}$ | $V_{cn}$ | $V_{ab}$ | $V_{bc}$ | $V_{ca}$ |
| $V_0$ | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| $V_1$ | 1 | 0 | 0 | $2/3\,V_{dc}$ | $-1/3\,V_{dc}$ | $-1/3\,V_{dc}$ | $V_{dc}$ | 0 | $-V_{dc}$ |
| $V_2$ | 1 | 1 | 0 | $1/3\,V_{dc}$ | $1/3\,V_{dc}$ | $-2/3\,V_{dc}$ | 0 | $V_{dc}$ | $-V_{dc}$ |
| $V_3$ | 0 | 1 | 0 | $-1/3\,V_{dc}$ | $2/3\,V_{dc}$ | $-1/3\,V_{dc}$ | $-V_{dc}$ | $V_{dc}$ | 0 |
| $V_4$ | 0 | 1 | 1 | $-2/3\,V_{dc}$ | $1/3\,V_{dc}$ | $1/3\,V_{dc}$ | $-V_{dc}$ | 0 | $V_{dc}$ |
| $V_5$ | 0 | 0 | 1 | $-1/3\,V_{dc}$ | $-1/3\,V_{dc}$ | $2/3\,V_{dc}$ | 0 | $-V_{dc}$ | $V_{dc}$ |
| $V_6$ | 1 | 0 | 1 | $1/3\,V_{dc}$ | $-2/3\,V_{dc}$ | $1/3\,V_{dc}$ | $V_{dc}$ | $-V_{dc}$ | 0 |
| $V_7$ | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |

**Figure 4.13** Switching pattern of voltage space vectors

- **Calculation of $T_0, T_1$ and $T_2$**

Beginning by the calculation of $T_0, T_1$ and $T_2$ in the sector 1

For generating a voltage vector $V_{ref}$ in sector-1 at a sampling $T_s$ time of , it requires two active voltage vectors and two null vectors. Let $V_1$ is the active voltage vector applied at fraction of time $\frac{T_1}{T_s}$ interval, and $V_2$ is the active voltage vector applied at time $\frac{T_2}{T_s}$ , and $V_0$ and $V_7$ are two null vectors which are applied at a time intervals of $\frac{T_0}{T_s}$ and $\frac{T_7}{T_s}$ respectively. Below figure represents the generation of vector $V_{ref}$ in sector-1.

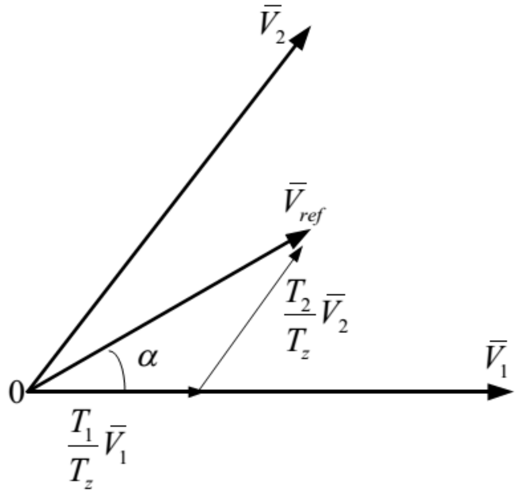



**Figure 4.14** Calculation of $V_{ref}$ in sector 1

By using the Volt-sec balance equation $V_{ref}$ calculated as follows

$$T_s V_{ref} = T_1 V_1 + T_2 V_2 \qquad (E\ 4.38)$$

$$V_{ref} = \frac{T_1}{T_s} V_1 + \frac{T_2}{T_s} V_2 \qquad (E\ 4.39)$$

$$T_s = T_1 + T_2 + T_n \qquad (E\ 4.40)$$

Where $T_n = T_0 + T_7$ and $|V_1| = |V_2| = |V_3| = |V_4| = |\ V_5| = |V_6| = |V_0| = |V_7| = \frac{2}{3} V_{dc}$ and

$0 \leq \alpha \leq \frac{\pi}{3}$

$$T_s \left| V_{ref} \right| \begin{bmatrix} cos\alpha \\ sin\alpha \end{bmatrix} = T_1 \frac{2}{3} V_{dc} \begin{bmatrix} 1 \\ 0 \end{bmatrix} + T_2 \frac{2}{3} V_{dc} \begin{bmatrix} cos\frac{\pi}{3} \\ sin\frac{\pi}{3} \end{bmatrix} (E\ 4.41)$$

Separate real and imaginary parts from the above equation, then

$$T_s \left| V_{ref} \right| cos\alpha = \frac{2}{3} V_{dc} T_1 + \frac{2}{3} V_{dc} T_2 cos\frac{\pi}{3} \qquad (E\ 4.42)$$

$$T_s \left| V_{ref} \right| sin\alpha = \frac{2}{3} V_{dc} T_2 sin\frac{\pi}{3} \quad (E\ 4.43)$$

$T_1$ and $T_2$ are calculated as follows:

$$T_1 = \frac{|V_{ref}|T_s sin\left(\frac{\pi}{3} - \alpha\right)}{\frac{2}{3}V_{dc} sin\frac{\pi}{3}} \quad (E\ 4.44)$$

$$T_2 = \frac{|V_{ref}|T_s sin(\alpha)}{\frac{2}{3}V_{dc} sin\frac{\pi}{3}} \quad (E\ 4.45)$$

$$T_0 = T_s - T_1 + T_2 \quad (E\ 4.46)$$

- **Determination of all the commutation time of all the switcher devices from $\boldsymbol{S_1\ to\ S_7}$**

The calculation of these magnitudes in any other sector gives with $n = \{1,2,3,4,5,6,7\}$,

$$T_s|V_{ref}|\begin{bmatrix} cos\alpha \\ sin\alpha \end{bmatrix} = T_1 \frac{2}{3} V_{dc} \begin{bmatrix} \cos\,(n-1)\frac{\pi}{3} \\ \sin\,(n-1)\frac{\pi}{3} \end{bmatrix} + T_2 \frac{2}{3} V_{dc} \begin{bmatrix} cosn\frac{\pi}{3} \\ sinn\frac{\pi}{3} \end{bmatrix} \quad (E\ 4.47)$$

Separate real and imaginary parts from the above equation, then:

$$T_S|V_{ref}|cos\alpha = \frac{2}{3}V_{dc}T_1 \cos(n-1)\frac{\pi}{3} + \frac{2}{3}V_{dc}T_2 cosn\frac{\pi}{3} \quad (E\ 4.48)$$

$$T_S|V_{ref}|sin\alpha = \frac{2}{3}V_{dc}T_1 \sin(n-1)\frac{\pi}{3} + \frac{2}{3}V_{dc}T_2 sinn\frac{\pi}{3} \quad (E\ 4.49)$$

Then,

$$T_1 = \frac{\sqrt{3}T_s|V_{ref}|\sin\left(n\frac{\pi}{3} - \alpha\right)}{V_{dc}} \quad (E\ 4.50)$$

$$T_2 = \frac{\sqrt{3}T_s|V_{ref}|\sin\left(\alpha - \frac{(n-1)\pi}{2}\right)}{V_{dc}} \quad (E\ 4.51)$$

And $$T_0 = T_s - T_1 + T_2$$

SVPWM and SPWM, the SVPWM method is self-instantaneous of the time at the value of the revolutions, is reduced, the total of the harmonics is also reduced and finally, this method allows a better use of the DC voltage bus.

The motor parameters we use are:

$R_s = 0.55\ ohm$

$L_s = 0.0075H$

$Voltage\ constant\ K_V = 3.351\ Vpeak/krpm$

$Torque\ constant\ K_t = 0.032\ N.m/Apeak$

$Back\ emf\ flat\ area\ (degrees) = 120$

$T_j = 0.0000115\ Kg.m^2$

$T_f = 0.0001\ N.m$

$Poles = 4$

$Friction\ coefficient = 0N.m.s$

These data represent the parameters that allow us to perform motor control using the space vector width modulation technique.

## 4.4 Simulation Results

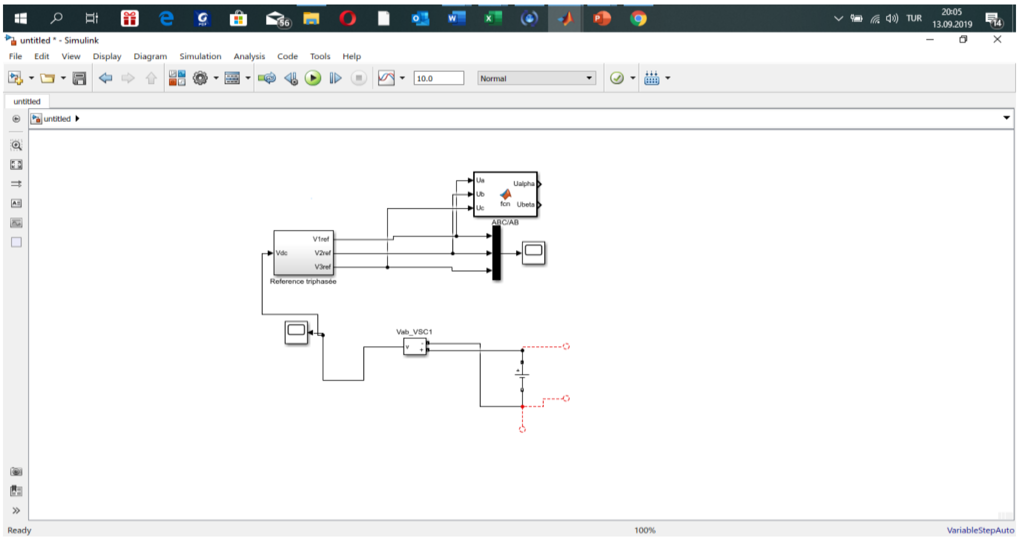
The overall system consists of 5 main parts that provide the desired voltage with the desired wave characteristics to allow rotation of the BLDC motor.

These 5 parts are: the three-phase reference block, the direct Park transformation block, the PWM vector space block, the inverter system and the BLDC motor.

These blocks are interconnected with each other in a progressive manner:

- ❖ **Three-phase block**

**T**he three-phase block figure is drawn below from matlab/Simulink software.



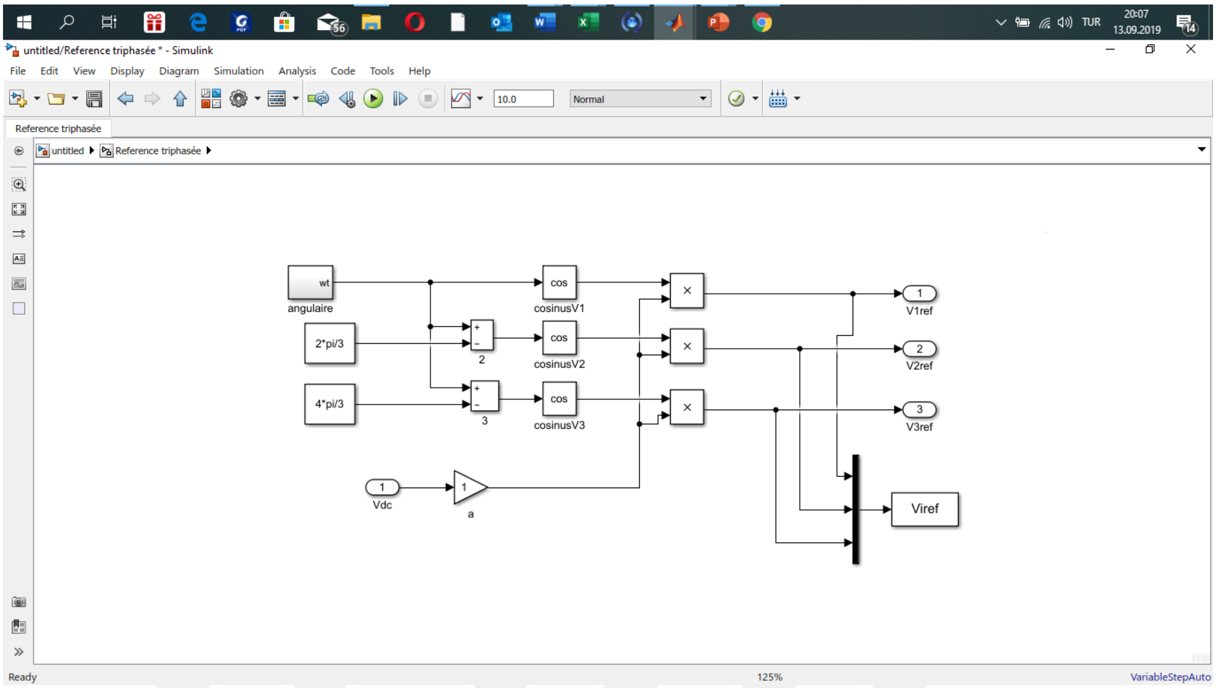



**Figure 4.15** Three phase block to produce $V_{ref}$

The BLDC machine when operating in motor mode receives a voltage to produce a torque or to generate a movement in general. In the practical case, the BLDC motors are three-phase motors, which means that they are powered by three phases. The characteristics of the three-phase currents and voltages which serve to supply the motor must have very different characteristics. Thus, for this purpose, a DC voltage source $V_{DC}$ is used whose role is to supply a DC voltage, the standard of which will be the standard of the voltages of the three-phase block. The three-phase block contains alternating voltages spaced from each other by 60º.

$$V_{1ref} = V_{DC} coswt$$

$$V_{2ref} = V_{DC} \cos\left(wt - \frac{2\pi}{3}\right)$$

$$V_{3ref} = V_{DC} cos\left(wt - \frac{4\pi}{3}\right)$$

The voltages coming from the three-phase block will then be transferred to the Park transformation block in order to obtain the tensions in the Park structure.

### ❖ The Park Direct Transformation Block

When using the SVPWM technique, it is necessary to obtain the reference vector. That reference vector must be transformed by using the Park transformation frame. Figure 4.16 shows that block.

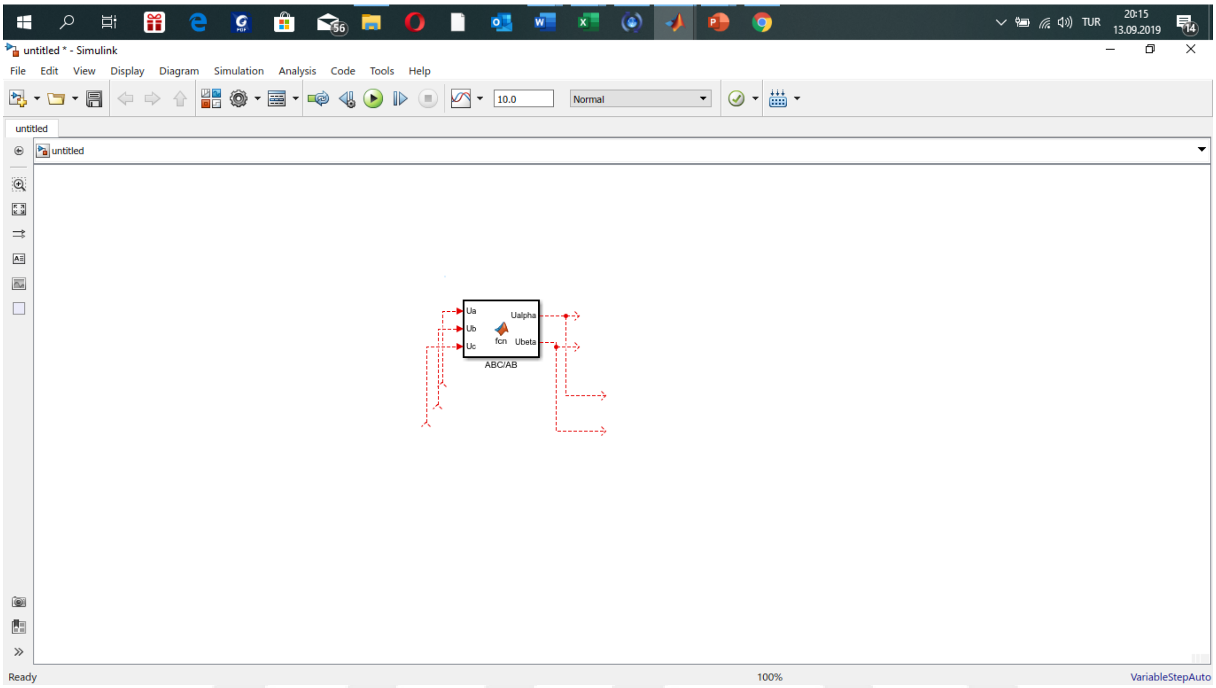



**Figure 4.16** Park Transformation block using a Fcn function

The reference vector V ref is obtained after obtaining the voltages in the Park reference. We thus obtain two the $V_\alpha$ and $V_\beta$ after transformation by this block. The equations use to get these magnitudes have been explained in the past paragraphs. The importance of synthesizing the $V_\alpha$ and $V_\beta$ tensions lies in the fact that the space vector pulse width modulation block uses data from the state of these two voltages to allow the sequential power supply of the motor.

In the MATLAB / Simulink block, we will use a function Fcn that allows to obtain these two tensions.

The following code is what Fcn function process to produce voltages in the reference frame of Park.

```
function [Ualpha,Ubeta]= fcn(Ua,Ub,Uc)
% This block supports an embeddable subset of the MATLAB language.
% See the help menu for details.

Ualpha=2/3*(Ua-0.5*Ub-0.5*Uc);
Ubeta=2/3*(sqrt(3)/2*Ub-sqrt(3)/2*Uc);
```

## ❖ The Space Vector Pulse Width Modulation Block (SVPWM)

The space vector PWM block is the most important block in the control system. It is represented in figure 4.17.

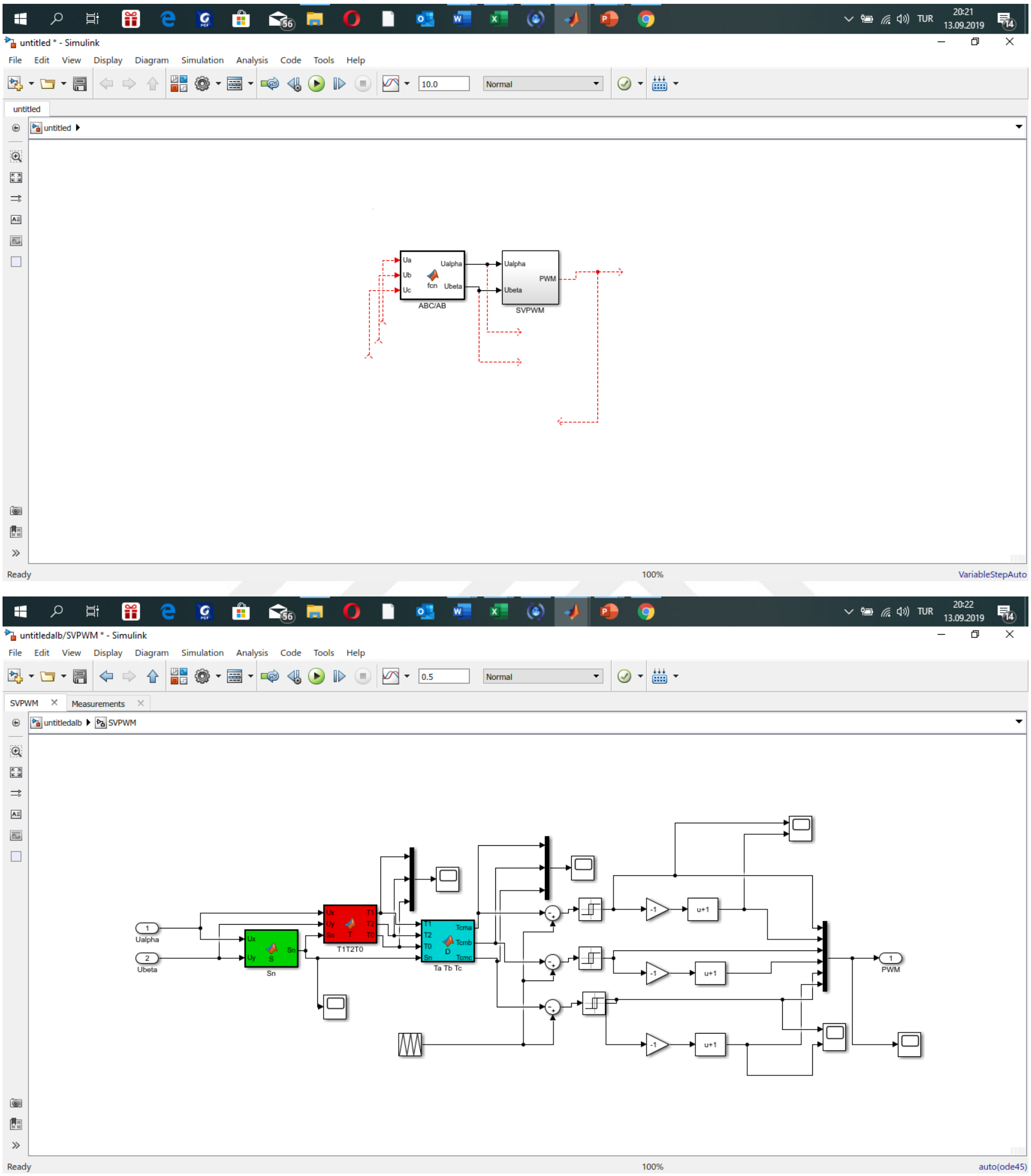



**Figure 4.17** Space vector width modulation structure block

This block works in order to generate pulsed signals whose state makes it possible to control the inverter system. The SVPWM method uses a diagram defined by 6sectors which contain the reference vector $V_{ref}$ determined by $V_{\alpha}$ and $V_{\beta}$. Each sector is determined by two vectors that each determines the state of the inverter system and the time that the inverter system in this state. The SVPWM block therefore uses three functions that ultimately influence the gate of the inverter system.

### ❖ The inverter system

The role of the inverter system is to convert the voltage of the DC source into a cyclic three-phase voltage system of variable waveform.

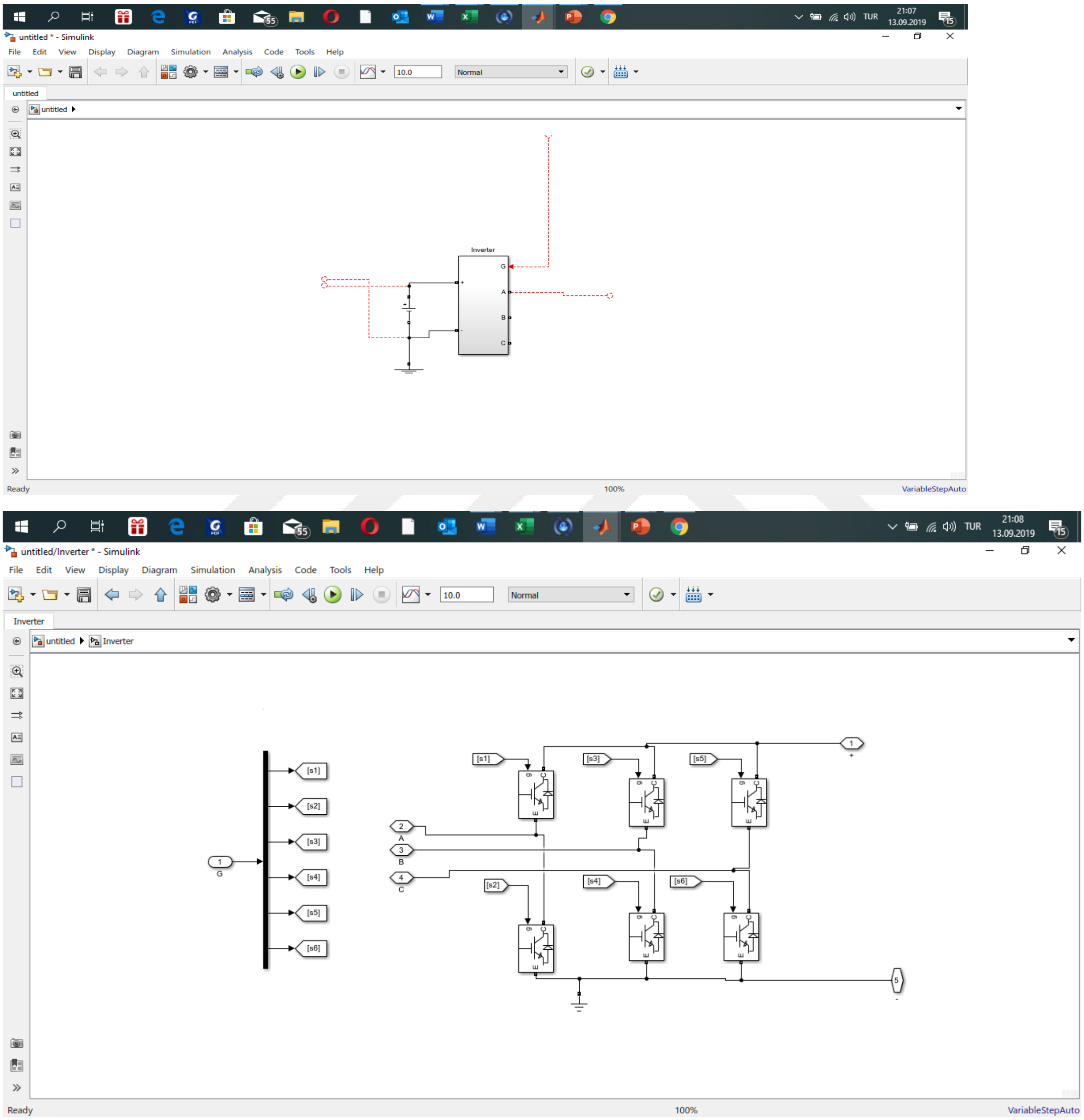



**Figure 4.18** Inverter system

Figure 4.18 shows the inverter system contains a system of six IGBT transistors. Each transistor contains a part called gate which allows the triggering of each transistor when it is excited by the modulation signal of the pulse width. The opening and the closing of each excited devices are going to produce different levels of voltage and energize two of three phases or wind of the stator motor.

The following part presents the simulation results of the Sensorless speed control of a BLDC motor by using the space vector width modulation techniques. We present the plot of the mechanical speed, the back electromotive force, the electromagnetic torque and stator current. The load torque is a constant which has a value of 0.13 Nm. The motor has been simulated before, so we choose a motor with simulated characteristics.

$R_s = 0.55\ ohm$

$L_s = 0.0075H$

$Voltage\ constant\ K_V = 3.351\ Vpeak/krpm$

$Torque\ constant\ K_t = 0.032\ N.m/Apeak$

$Back\ emf\ flat\ area\ (degrees) = 120$

$T_j = 0.0000115\ Kg.m^2$

$T_f = 0.0001\ N.m$

$Poles = 4$

$Friction\ coefficient = 0N.m.s$

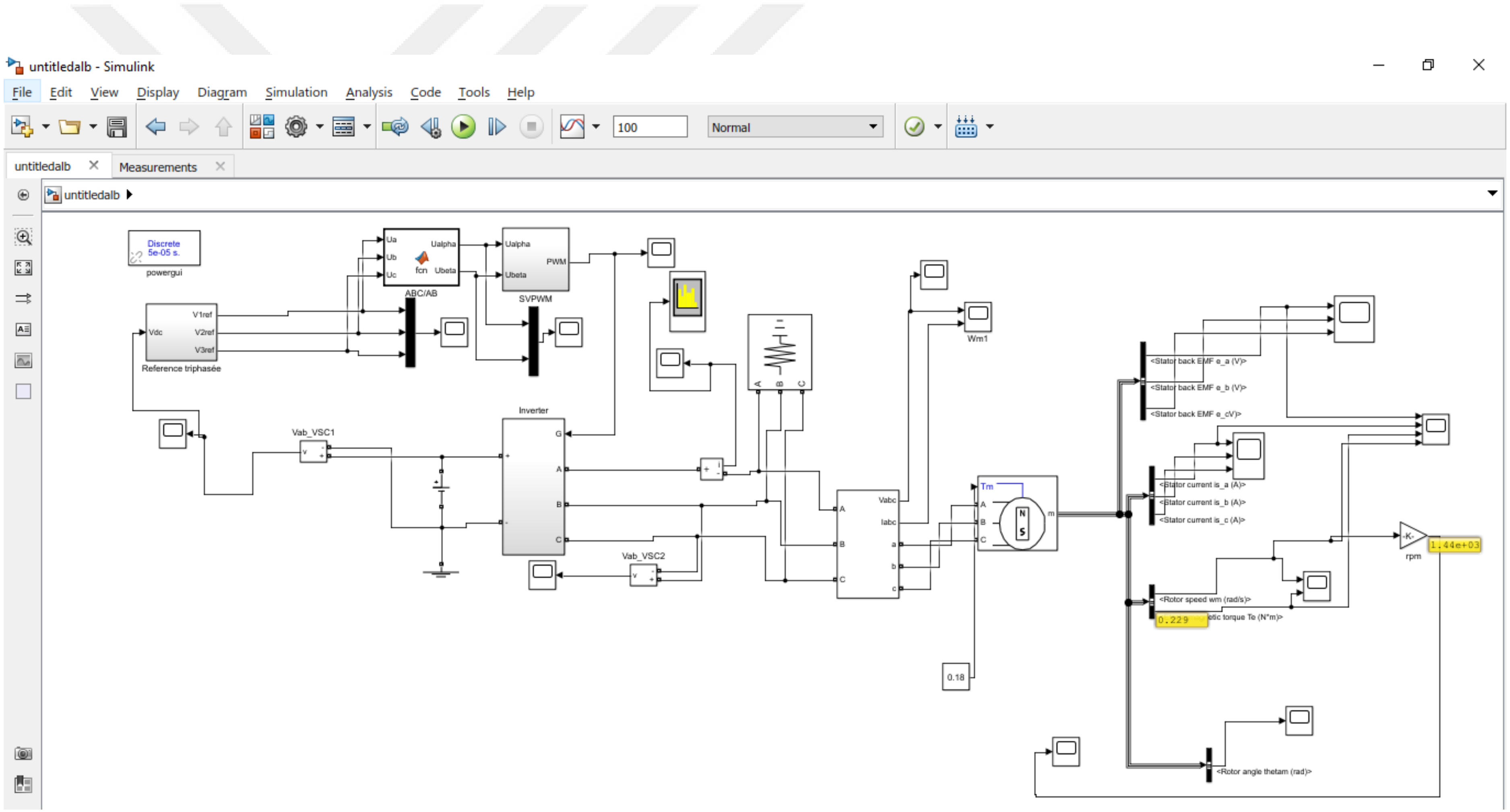


**Figure 4.19** Simulink representation of the all system

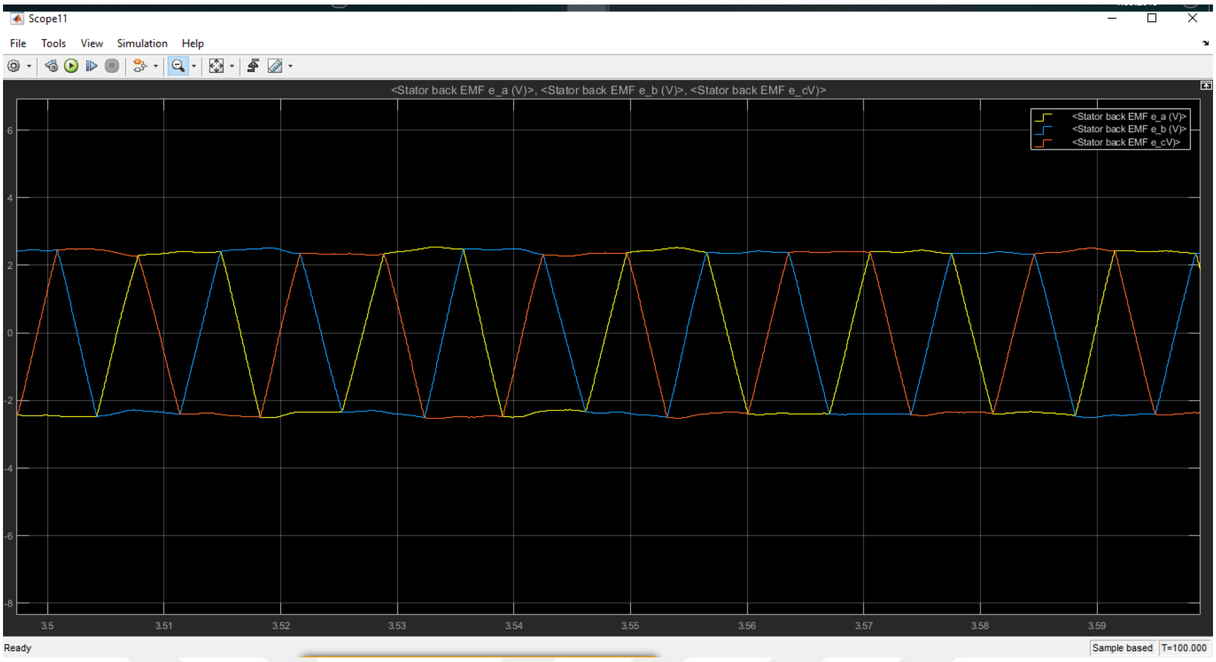



**Figure 4.20** Trapezoidale Back EMF

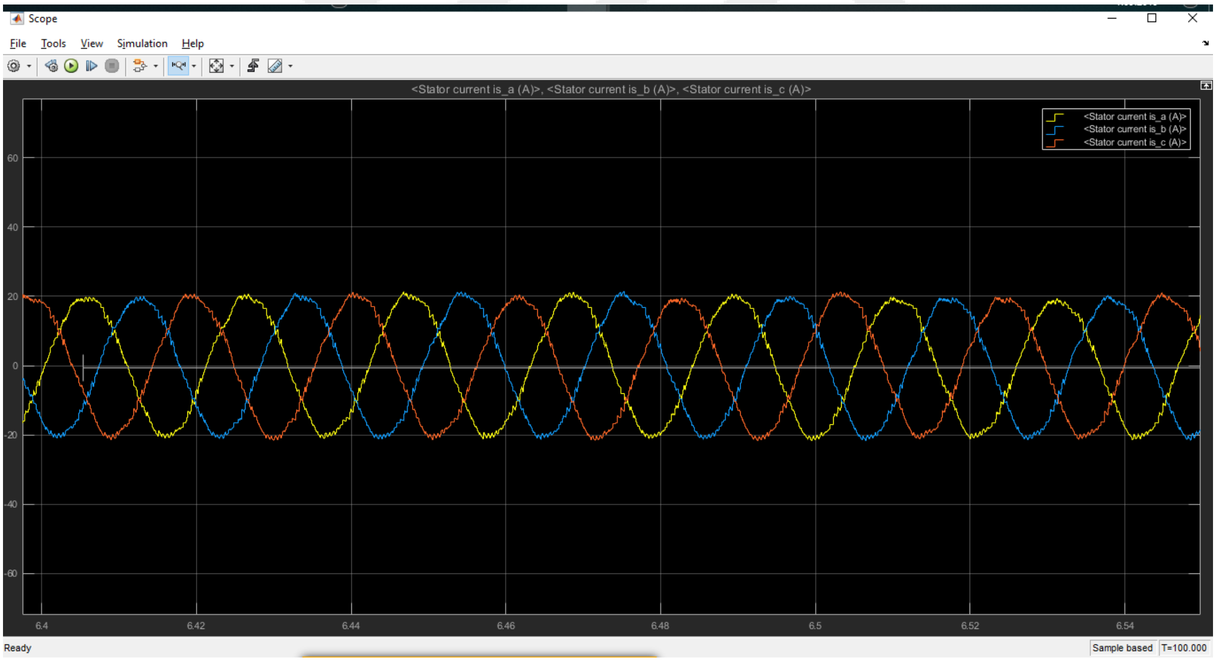



**Figure 4.21** Stator Current representation

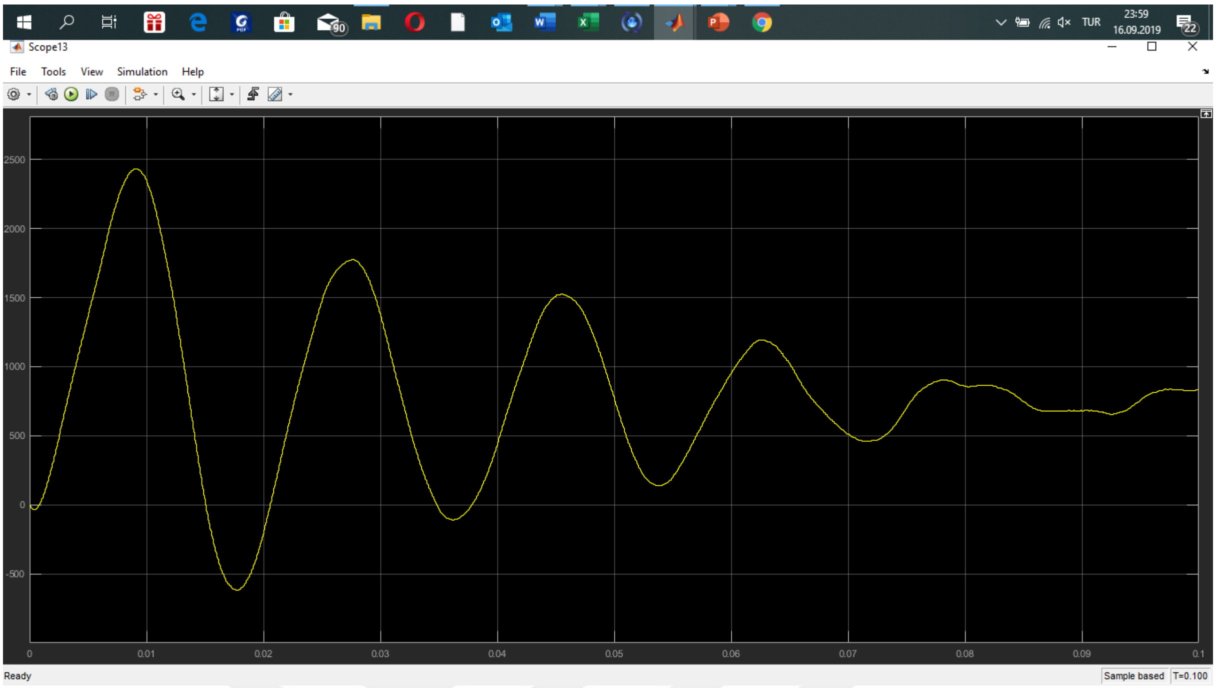
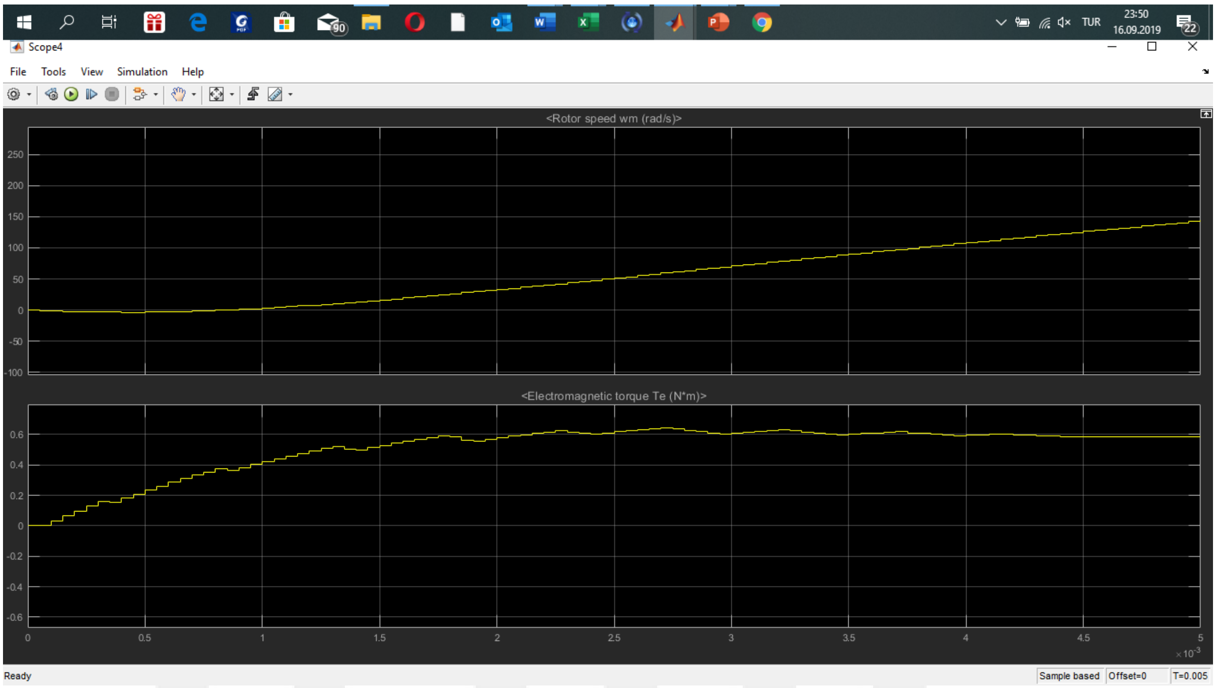
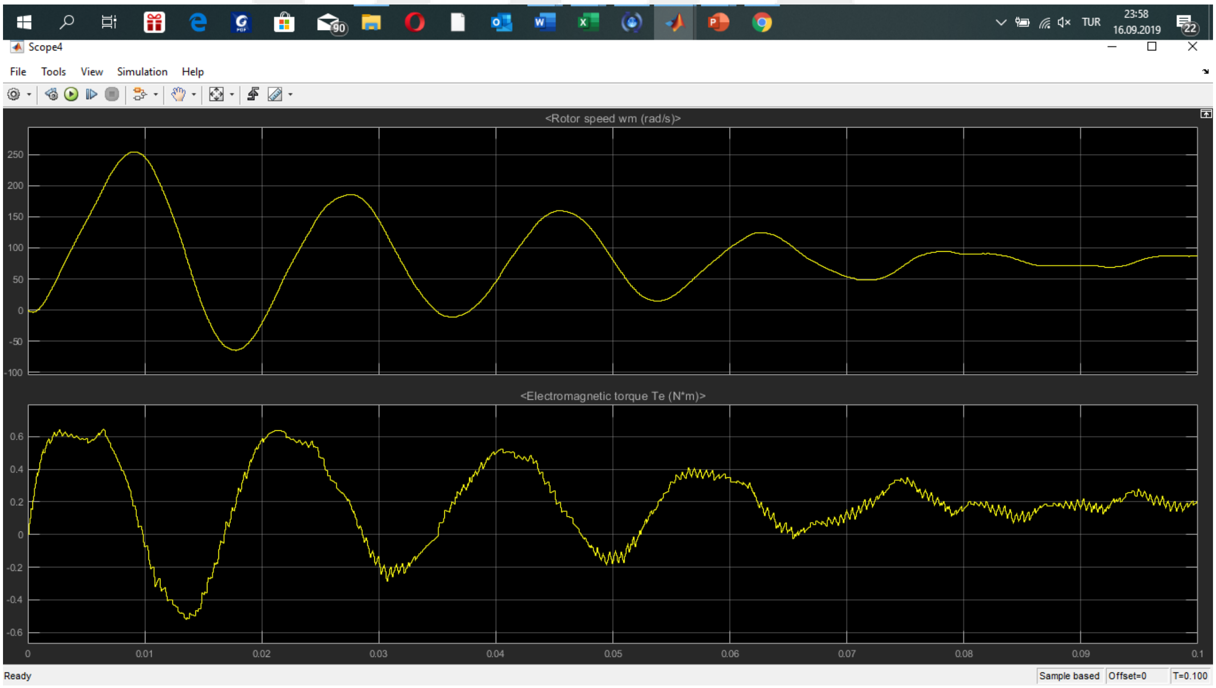


**Figure 4.22** Speed representation between $[0 - 0.1]$ *second*

In this picture, the representation of the rotor speed has been displayed. We can see the waves which occurs at the starter of the motor and those waves progressively disappear and the speed of the motor stabilize at a given value.




**A) Motor torque wave forms representation**




**B) Speed wave forms representation**

**Figure 4.23** Electromagnetic torque (A) and speed representation (B) between $[0 - 0.005]$ *second and* $[0 - 0.1]$ *second*

**DISCUSSION ACCORDING THE WAY THE MOTOR REACTING TO CHANGING OF THE VALUE OF THE RESISTOR VALUE WITH POWERGUI SET TO 0.5**

- ❖ Rs is set to 0.55 ohm

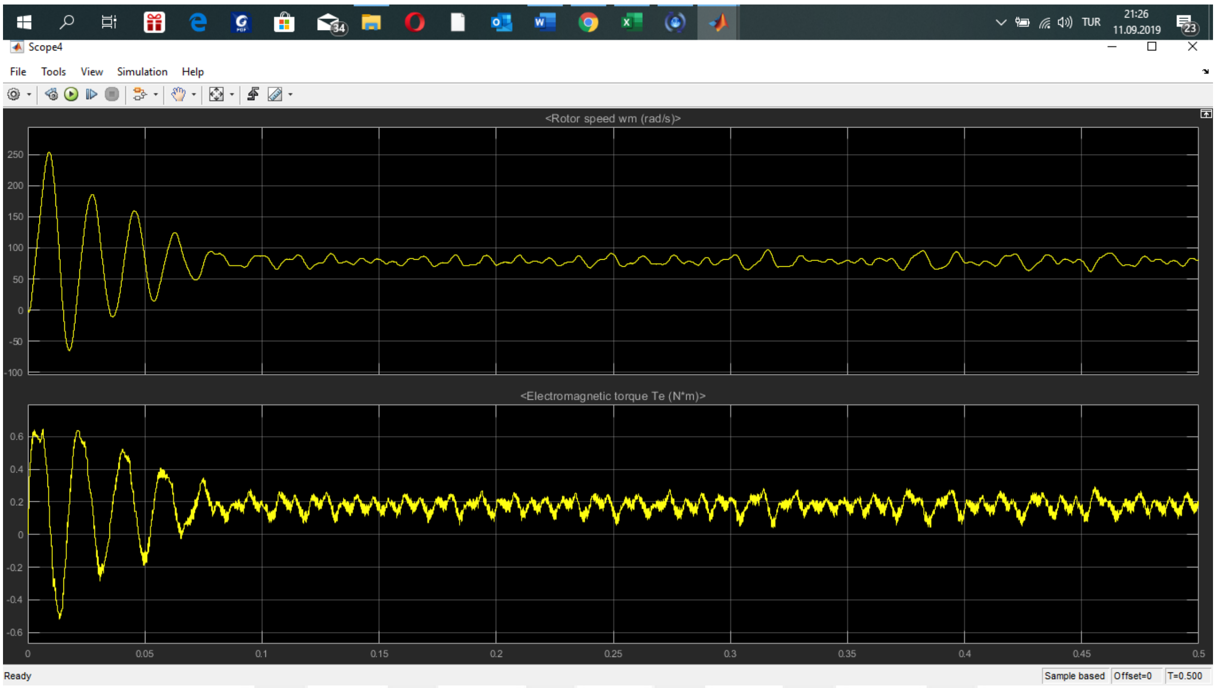



**Figure 4.24** Electromagnetic torque and speed representation between $[0 - 0.5]$ $second$ when Rs=0.55 Ω

- ❖ Rs is set to 0.7 ohm until 1.2 ohm

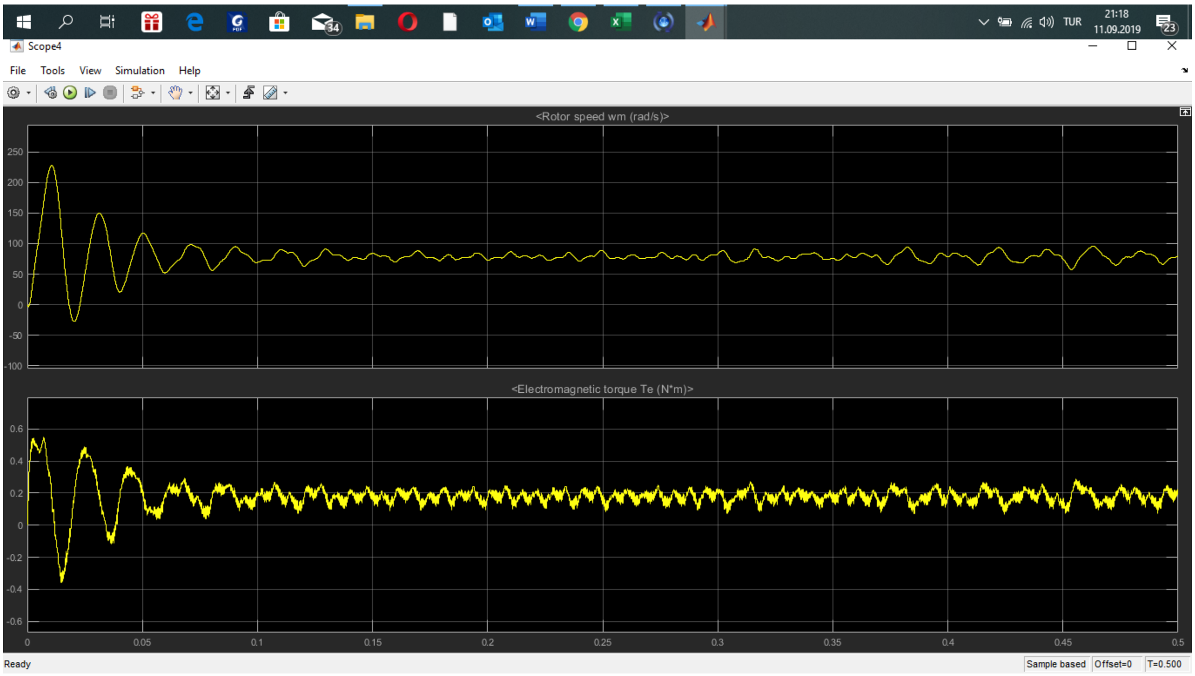



**Figure 4.25** Electromagnetic torque and speed representation between $[0 - 0.5]$ $second$

❖ Rs is set to 1.3 ohm

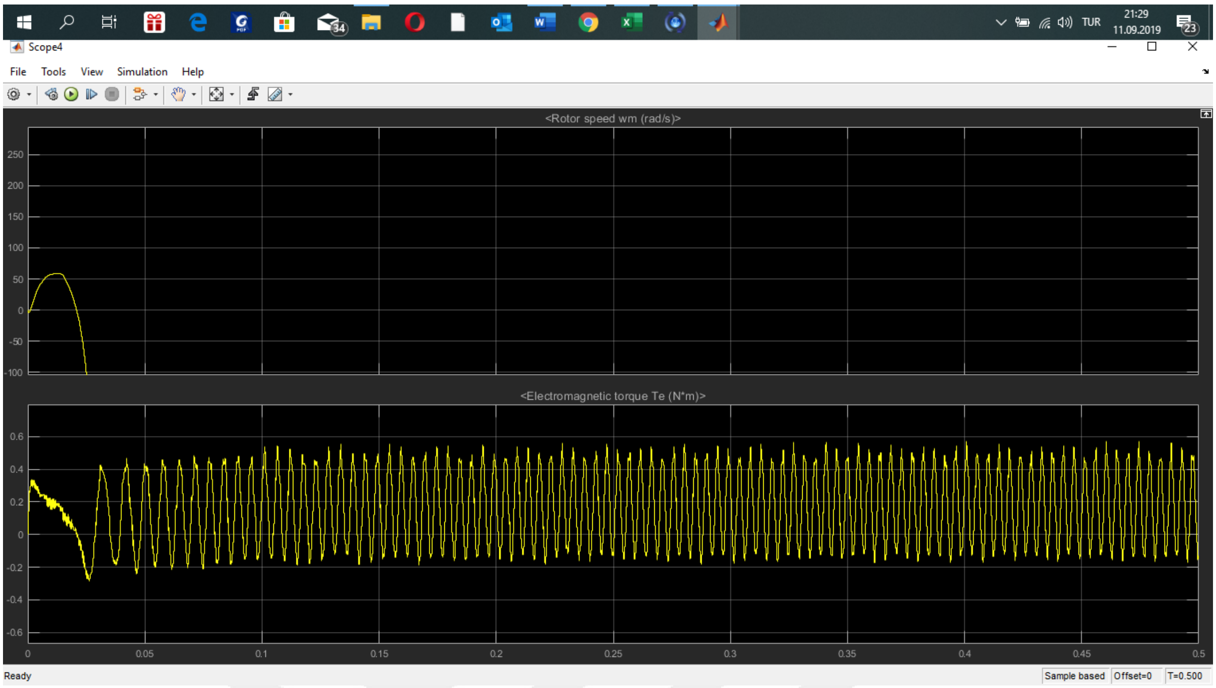



**Figure 4.26** Electromagnetic torque and speed representation between $[0 - 0.5]$ *second* when Rs=1.3 Ω

## Discussion

Related to the control that has been performed and according to the data obtained concerning the variation of resistance of the stator of the motor. We have noticed that when the resistance of the stator varies by increasing, the characteristic of the speed and the electromagnetic torque of the motor varies.

When the resistance of the stator $R_s$= 0.55 Ω, the motor reaches the speed of 2468 rpm before stabilizing at 1500 rpm and the electromagnetic torque exceeds 0.6 Nm before fluctuating between 0.2 Nm and 0.18 Nm

When $R_s$ = 0.7 Ω up to 1.2 Ω, the motor reaches the maximum speed of 2150 rpm before stabilizing at 1500 rpm. The maximum electromagnetic torque is less than 0.6 Nm before fluctuating between 0.2 Nm and 0.18 Nm

In other words, when $0.55 \leq R_s \leq 1.2$ [Ω], the rotation speed of the motor and the electromagnetic torque stabilize very quickly, and the peaks at startup are more or less reduced and the stabilization of the torque and speed is faster as $R_s$ gets closer to 1.2 Ω.

When $R_s$ exceeds 1.2Ω, there is a large variation in speed and electromagnetic torque. The speed reaches 478 rpm then returns to zero and becomes negative. The electromagnetic torque oscillates uncontrollably. In other words, beyond 1.3 Ω, if the inductance remains constant, the motor becomes uncontrollable.

The values of the stator resistors that we find on the BLDC motors are not the maximum values.

The comparison that we can make about our system and the previous systems that we already saw and studied is that our system is effective but not like these systems. According the responsiveness of our system, it is almost the same with system commanded by PID controllers.

PID controller make the system to stabilize rapidly but not handle the torque ripple for the case of brushless direct current motors because they are nonlinear systems. On the other side, our system is well designed to handle torque ripple because the model equation is based on the fact the system to be controlled is a nonlinear one.

The use of space vector pulse width modulation technique combinate to Park frame and electronic calculus system for the energization of stator magnet gives the ability to the controller to make the motor being efficient to reach high speed without losing synchronization and rapidly stabilize.

## Recommendations

The variation of the resistance upwards gives good results when we analyse the response of the torque and the speed. So, to obtain a faster response of the torque and the speed which stabilizes much more quickly on the nominal value of operation. In this variation, the load torque must be considered so that it is not greater than the electromagnetic torque in which case the motor would pick up and operate in generator mode.

In other words, the variation of the resistance beyond a certain extent switches the mode of operation of the machine from a motor mode to the generator mode.

Thus, to operate a BLDC motor in both motor mode and generator mode, it would be possible to install a system of resistors mounted in parallel with each other and having different values. Their individual or group operation would directly affect the torque and speed of the motor. Resistance greater than the maximum resistance would result in generator mode operation. Resistor value below the maximum value would result in motor mode operation. This kind of system may Works but when we analyse the system carrefuly, the association of resistors will produce much more copper losses since the resistors will be crossed by active cuurent. More the resistors number will result in an effect of the motor weight.

By analysing the studies made by Dr Ismail Temiz [31], we can influence the stator resistor by controlling the stator current of the axis d.

$V_d = L_a \frac{d}{dt} i_d + R_a i_d + K_e \omega_m$ (a)

We acknowledge that $T = j \frac{d\omega}{dt} + f\omega$ (b)

Also $T = \frac{3}{4} K_t * pole\ number * i_d$

The pole number is set to be 2. Then $T = 1.5 K_t i_d$ and from (b) we can writte:

$1.5 K_t i_d = j \frac{d\omega}{dt} + f\omega$ , then $\frac{d\omega}{dt} = \frac{-f}{J} \omega + \frac{1.5K_t}{J} i_d$ (c),

From a and c,

We obtain that matrice

$$\begin{bmatrix} \dot{\omega}_m \\ i_d \end{bmatrix} = \begin{bmatrix} \frac{-f}{J} & \frac{1.5K_t}{J} \\ \frac{-K_e}{L_a} & \frac{-R_a}{L_a} \end{bmatrix} * \begin{bmatrix} \omega_m \\ i_d \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{1}{L_a} \end{bmatrix} * V_d$$

$$y = \begin{bmatrix} 1 & 0 \end{bmatrix} * \begin{bmatrix} \omega_m \\ i_d \end{bmatrix}$$

The control of brushless Direct Current motors is a branch which is in current development due to the importance and relevant characteristics of these types of electric motors. The fact that brushless motors have not brushes is a great advantage because they are not likely to have frequent damages as the normal DC motors. So, after having resolved the problem related to the need of a development of a very good electronic system capable to command the switchers of the inverter system efficiently, we can develop other type of method to control the way the machine works either like an electrical generator or a motor as we discussed up.

The field of control of BLDC motors has open the way to create diverse type of techniques of control. These last years, we have witnessed the apparition of powerful control methods such as field-oriented control, space vector pulse width modulation, slide mode control. In our study, after having shown a range of the actual techniques which are used in the control field, we took the decision to make an application of the space vector width modulation technique.

It shown us that the advantages using that technique compared to other technique. Even though the equation that we use are quite a little bit complicated, the implementation of the techniques is not so difficult, and it gives good result.

## REFERENCES


[1] José C.G-R., Ernesto V-S., Jaime G-G. (2010) Position and Speed Control of Brushless DC Motors Using Sensorless Techniques and Applications Trends.2010 (Sensors 2010), July, 10, 6901-6947.

[2] Farah, S. (2013) Brushless Motors Identification and Command for small drone. Toulouse, France.

[3] M. Godoy, S., Felix, A.F. (2017) Modeling Power Electronics and Interfacing Energy Conversion Systems. ISBN 9781119058472(epub) Hoboken, NJ, USA,

[4] J. Holtz (2006). Sensorless Control of Induction Machines: With or Without Signal Injection, IEEE Trans. Ind: Electrton.,53:7-30

[5 Georges Nagy (1960) The Hysteresis Motor Gill University, Montréal, Canada

[6] J.J. Nitao, E.T. Scharleman, and B.A. Kirkendall (2009) "Equivalent Circuit Modelling of Hysteresis Motors", Lawrence Livermore, National Laboratory, 21 July 2009, USA

[7] Haute Ecole Spécialisée de Suisse Occidentale, IAI, Systèmes électromécaniques Les Moteurs pas à pas", Suisse

[8] Sophie Sekalala, (2006) "Performance Of A Three-Phase Permanent Magnet Motor Operating As A Synchronous Motor and a Brushless DC Motor" August 2006, City University, New-York

[9] Freescale Semiconductor, Inc.,"3-phase PM Synchronous Motor Torque Vector Control Using 56F805", Designer Reference Manual, DRM018/D Rev.0,03/2003

8[10] Ramu Krishnan, (2010) "Permanent Magnet Synchronous and Brushless DC Motor Drives", Virgina Tech, Blacksburg, Virginia, USA

[11] Brushless DC Motor Control using the LPC2141 Application Note; AN10661, NXP Semiconductors: Eindhoven, the Netherlands, October 2007.

[12] 3-Phase BLDC Motor Control with Hall Sensors using 56000/E Digital Signal Controllers Application Note; AN1916, Freescale Semiconductor: TX, USA, 2005.

[13] Chang-Liang (2012) "Permanent Magnet Brushless DC Motor Drives and Controls" 2012, Xia Tianjin University, P.R. China.

[14] Leonid Reznik. (1997) "Fuzzy Controlers”, Victorya University of Technology, Melbourne, Australia.

[15] Xia, C. L., Liu, D., Wang, Y. F., et al. (2007) Control of brushless DC motors using fuzzy set base dimmune feedback PID controller. Transactions of China Electrotechnical Society, 22(9), 68–73 (in Chinese).

[16] Chen, W., Xia, C. L., (2006) Sensorless control of brushless DC motor based on fuzzy logic. IEEE Proceedings of the World Congress on Intelligent Control and Automation, China, 6298–6302.124 Permanent Magnet Brushless DC Motor Drives and Controls

[17] Xia, C. L., Xiu, J. (2006) Sensorless control of switched reluctance motor based on ANFIS. Lecture Notes in Computer Science, 234:645–653.

[18] Rubaai, A., Ricketts, D., Kankam, M. D. (2001) Experimental verification of a hybrid fuzzy control strategy for a high-performance brushless DC drive system. IEEE Transactions on Industry Applications, 37(2), 503–512.

[19] Kaushal Kishor, Sheela Tiwari,"Speed Control of a Brushless DC Motor Using Neural Network Based MRAC"NIT, International Journal of Industrial Electronics and Electrical Motorering, ISSN: 2393-2835, India, 2017.

[20] Lin, C. L., Jan, H. Y., Shieh, N.C. (2003) GA-Based multi-objective PID control for a linear brushless DC motor. IEEE Transactions on Mechatronics, 8(1), 56–65.

[21] Xia, C. L., Liu, D., Wang, Y. F. (2007) Artificial neural network control of brushless DC motor based on immune feedback adaptive learning. Journal of Tianjin University, 40(10), 1235–1240 (in Chinese).

[22] Xia, C. L., Fang, H. W., Chen, W., et al. (2006) Ant colony algorithm based fuzzy control for a brushless DC motor. IEEE Proceedings of the World Congress on Intelligent Control and Automation China,6498–6502.

[23] Wang, Y. F., Xia, C. L., Zhang, M. H., et al. (2007) Adaptive speed control for brushless DC motors based ongenetic algorithm and RBF neural network. IEEE International Conference on Control and Automation China, 1219–1222.

[24] Liu, D., Xia, C. L., (2007) Control of brushless DC motor using fuzzy set based immune feedback PID controlle. IEEE International Symposium on Industrial Electronics, Spain, 1045–1049.

[25] Maoqing Zhang, Zhongcheng Yu, Hongcai Huan and Yanrong Zhou, March (2007)," The Sliding Mode Variable Structure Control Based on Composite Reaching Law of Active Magnetic Bearing" ICIC International 2008 ISSN 1881-803X pp. 59-63

[26] Xia, C. L., Liu, J. H., Yu, W., et al. (2005) Variable structure control of BLDCM based on extended state observer. IEEE International Conference on Mechatronics and Automation, Canada, 568–571.

[27] Lim, K. W., Low, T. S., Rahman, M. F. et al. (1991) A discrete time variable structure controller for a brushless DC motor drive. IEEE Transactions on Industrial Electronics, 38(2), 102–107.

[28] José C.G-R.; Ernesto V-S.; Jaime G-G. (2010) Position and Speed Control of Brushless DC Motors Using Sensorless Techniques and Applications Trends. (Sensors 2010), July 2010,10,6901-6947.

[29] Johnson, J.P., Ehsani, M., Guzelgunler, Y. (1999) Review of Sensorless Methods for Brushless DC. In Proceedings of the 1999 IEEE Industry Applications Conference (Thirty-Fourth IAS Annual Meeting), Phoenix, AZ, USA, October 1999; Volume 1. pp. 143-150

[30] Moreira, J.C. (1996) Indirect Sensing for Rotor Flux Position of Permanent Magnet AC Motors Operating Over a Wide Speed Range. IEEE Trans. Ind. Appl. 1996, *32,* 1394-1401.

[31] Ismail T., Selçuk A.(2000) Investigating The Brushless DC Motors By State Space Approach.M.Ü. Fen Bilimleri Dergisi, Sayı:16,2000 pp. 237-252

[32] Antonio F.,Anthony Mallet (2019) "Adaptive Closed-Loop Speed Control of BLDC Motors with Applications to Multi-Rotor Aerial Vehicles",LAA-CNRS, Toulouse University,CNRS,Toulouse,France.

[33] P.suganthi,S.nagapavithra (2017) "Modeling and Simulation of Closed Loop Speed Control for BLDC Motor" Mahendra Engineering College, Mahendhirapuri, Mallasamudram, Namakkal DT- 637503

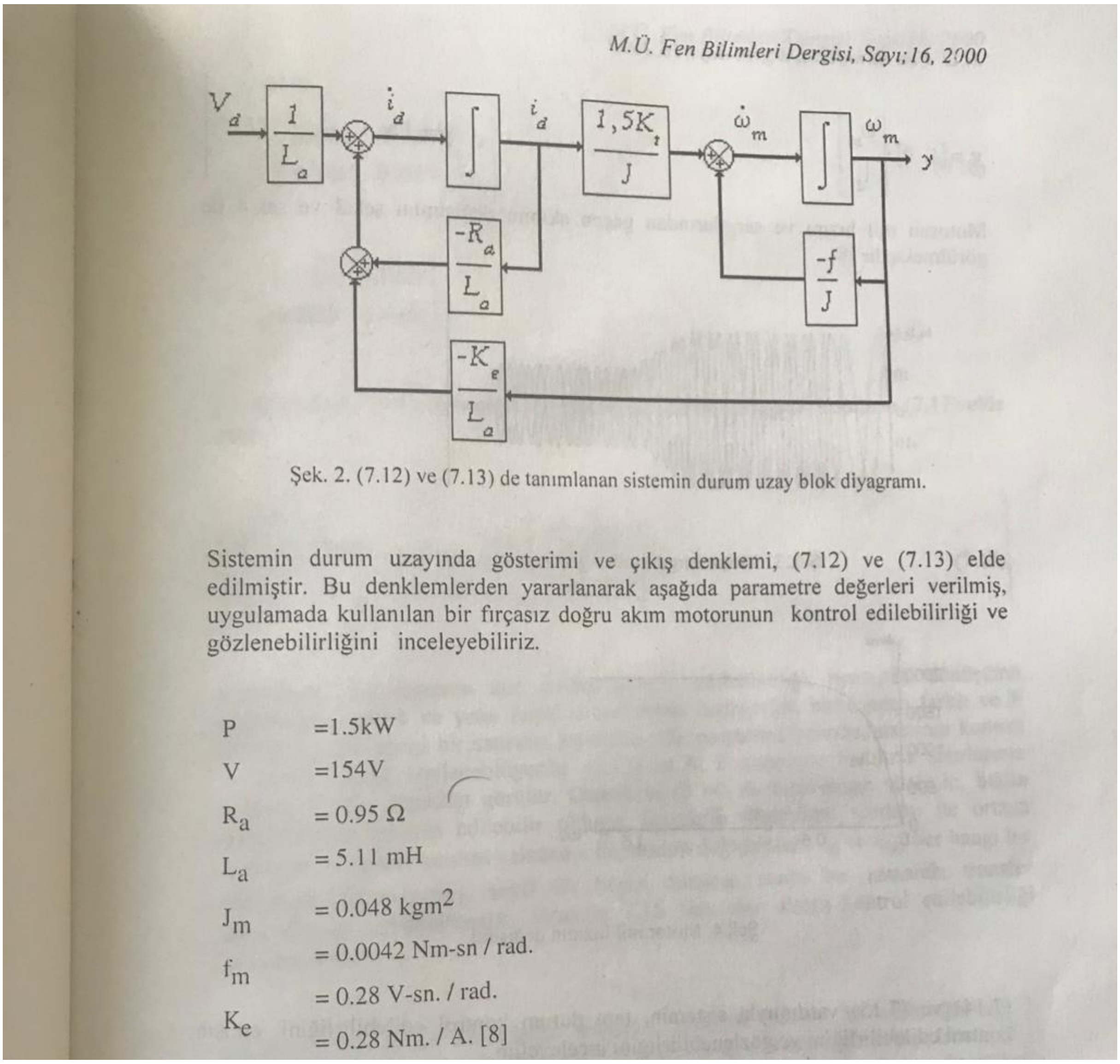
[34] Subrat S.,Brajesh K.,Nirbhar N., (2017) "Controller Design for Closed Loop Speed Control of BLDC Motor" Birla Institute of Technology, Mesra,

[35] Alejandra D.L.G.,Lizeth T.Luis A., ( 2018) "Speed Sensorless Robust Control for a Brushless DC motor" Metropolitan Autonomous University

[36] Poonam M.Y.,Gadgune S.,(2019) “Position and Speed Control of Brushless DC Motors using Sensorless Techniques: A Review”, International Journal of Engineering Research & Technology (IJERT), ISSN: 2278-0181, Vol. 8 Issue 01, January-2019

## Annexes

1. Ismail Temiz'in tanımlanan sistemin durum uzay blok dıagramını



M.Ü. Fen Bilimleri Dergisi, Sayı;16, 2000



Şek. 2. (7.12) ve (7.13) de tanımlanan sistemin durum uzay blok diyagramı.

Sistemin durum uzayında gösterimi ve çıkış denklemi, (7.12) ve (7.13) elde edilmiştir. Bu denklemlerden yararlanarak aşağıda parametre değerleri verilmiş, uygulamada kullanılan bir fırçasız doğru akım motorunun kontrol edilebilirliği ve gözlenebilirliğini inceleyebiliriz.

| | |
|---|---|
| P | =1.5kW |
| V | =154V |
| $R_a$ | = 0.95 Ω |
| $L_a$ | = 5.11 mH |
| $J_m$ | = 0.048 $kgm^2$ |
| $f_m$ | = 0.0042 Nm-sn / rad. |
| $K_e$ | = 0.28 V-sn. / rad. |
| | = 0.28 Nm. / A. [8] |

2. (A,B,C) to ( alpha,beta) block

```
function [Ualpha,Ubeta]= fcn(Ua,Ub,Uc)
% This block supports an embeddable subset of the MATLAB language.
% See the help menu for details.

Ualpha=2/3*(Ua-0.5*Ub-0.5*Uc);
Ubeta=2/3*(sqrt(3)/2*Ub-sqrt(3)/2*Uc);
```

3. Sn function

```
function Sn = S(Ux,Uy)
theta=atan2(Uy,Ux)*180/pi;
if theta>=0&&theta<60
Sn=1;
elseif theta>=60&&theta<120
Sn=2;
elseif theta>=120&&theta<180
Sn=3;
elseif theta>=-180&&theta<-120
Sn=4;
elseif theta>=-120&&theta<-60
Sn=5;
else Sn=6;
end
```

4. T function

```
function [T1,T2,T0]=T(Ux,Uy,Sn)
Ts=1/2000;
Udc=24;

X=sqrt(3)*Ts/Udc*Uy;
Y=sqrt(3)*Ts/2/Udc*(sqrt(3)*Ux+Uy);
Z=sqrt(3)*Ts/2/Udc*(-sqrt(3)*Ux+Uy);

if Sn==1
    T1=-Z;T2=X;
elseif Sn==2;
    T1=Z;T2=Y;
elseif Sn==3;
    T1=X;T2=-Y;
elseif Sn==4;
    T1=-X;T2=Z;
elseif Sn==5;
    T1=-Y;T2=-Z;
else T1=Y;T2=-X;
end

if T1+T2>Ts
    a=T1;b=T2;
    T1=a*Ts/(a+b);
    T2=b*Ts/(a+b);
end

T0=Ts-T1-T2;
```

5. D function

```
function [Tcma,Tcmb,Tcmc]=D(T1,T2,T0,Sn)
Ts=1/2000;
Udc=24;
ton1=0.5*T0;
ton2=ton1+T1/2;
ton3=ton2+T2/2;
```

```
if Sn==1
Tcma=ton1;Tcmb=ton2;Tcmc=ton3;
elseif Sn==2;
Tcma=ton2;Tcmb=ton1;Tcmc=ton3;
elseif Sn==3;
Tcma=ton3;Tcmb=ton1;Tcmc=ton2;
elseif Sn==4;
Tcma=ton3;Tcmb=ton2;Tcmc=ton1;
elseif Sn==5;
Tcma=ton2;Tcmb=ton3;Tcmc=ton1;
else Tcma=ton1;Tcmb=ton3;Tcmc=ton2;
end
```

## Curriculum Vitae

Alban Exauce Mouandza Mboungou

Zafer Mahallesi Adile Naşıt Bulvarı

Esenyurt/ Istanbul-Turkey

Mobile: 00905343825106

Email address: albanexaucee26@yahoo.fr

Nationality: Congolese

Day and place of birth: 26/09/1992 in Pointe-Noire – Republic of Congo

Single

### Work experience:

May 2015: SOGEF, Dakar, Senegal

Position: Technician Electromechanical

**Function: Maintenance of Groups Producing Cold ,refrigerant gas and liquid.**

July 2013: Dakar Dem Dik, Dakar, Senegal

Positon: Tehnician Electrotechnical

**Function: Maintenance of electrical systems for electronic buses**

### Education:

2017-2018: Master's Degree in Mechatronics Motorering University of Marmara, Istanbul, Turkey

2014-2015:Bachelor's Degree in Electrotechnics Speciality: Electromechanics, Refrigeration & Air-conditioning Dakar Higher Institute of Industrial Technology, Senegal

2013-2014: **Advanced Vocational Training Certificate in Electrotechnics** College of Entrepreneurship & Technical Development, Dakar (CETD, Le G15)

2011-2012: **Preparatory Classes in General Science of Motorering** École Polytechnique of Masuku University of Sciences and Techniques of Masuku, Gabon

2010-2011: **Science-based Baccalauréat in Mathematics-Physics** Lycée de l'Excellence de Franceville, Gabon.

## Personal skills and others:

Languages:

French: Native language

English: Fluent

Turkish: Fluent

Computing:

Internet Browsers (google chrome, internet explorer, mozilla firefox) Monitor: Keeping information update, put all necessary information Other programs: Proteus, FEMM, EPLAN (Microsoft office (word, Access, Excel, power point)

Personal interest: Reading, Social Networks, Learning other culture, Geography of French speaking countries.