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MASTER MEMORY

DOMAIN: Technology
SECTOR: Electronics
OPTION: Automatic and industrial computing
Theme

Control of a wind system connected to the electrical network and powering a mechanical load

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ملخص

الطاقة المتجددة تتيح إنتاج طاقة كهربائية لامركزية ، مما يساهم في تزويد منطقة معزولة بالطاقة اللازمة. الهدف الرئيسي من هذا العمل هو التحكم في منظومة طاقة الرياح على أساس محرك ذو تيار مستمر يقودها توربين متغير السرعة. يتم دراسة نموذج لكل مرحلة في سلسلة تحويل الطاقة. يتم توصيل مولد التيار المستمر بالشبكة الكهربائية من خلال محولين متتاليين(قاطع متناوب وعاكس)(DC-DC) و(AC-DC) ، كما أتاح لنا التحكم بواسطة منظم كلاسيكي PI التحكم في سرعة الماكينة لالتقاط أقصى طاقة للرياح(MPPT). بنفس الطريقة، تم ضبط جهد ناقل التيار المستمر عبر المحول الجانبي الرئيسي مما سمح لنا بتغذية حمولة متغيرة وحقن فائض الطاقة في الشبكة مع تغذية الحمولة مباشرة من الشبكة في حال عدم إنتاج التوربين لطاقة كافية .

الكلمات المفتاحيه : نظام تحويل طاقة الرياح , أقصى طاقة للرياح,التباطؤ الحالي, محول عاكس ,قاطع متناوب.
, PI, (AC-DC) , PWM, (DC-DC)

Résumé

L'exploitation des énergies renouvelables permet la production d'énergie électrique décentralisée, ce qui contribue à une solution pour alimenter une zone isolée avec l'énergie nécessaire. L'objectif principal de ce travail est de contrôler un système éolien basé sur une machine à courant continu entraînée par une éolienne à vitesse variable. Un modèle a été établi pour chaque élément constituant la chaîne de conversion d'énergie. L'aérogénérateur à courant continu est connecté au réseau électrique par l'intermédiaire de deux convertisseurs (DC/DC) et (DC/AC). En effet, le contrôle par un régulateur classique (PI) de la vitesse de la génératrice en agissant sur le DC/DC nous a permis de capter la puissance maximale du vent et réaliser ce qu'on appelle le fonctionnement en MPPT. De même un deuxième régulateur PI a été appliqué au convertisseur DC/DC pour garantir une tension du bus continu **constante**. Ce système éolien alimente en plus une charge mécanique basée sur une machine à courant continu dont la vitesse de rotation est contrôlée par un autre régulateur PI appliqué à un deuxième convertisseur DC/DC.

Mots clés : Système de conversion de l'énergie éolienne, Hacheur, Point de puissance maximale, Onduleur, PWM, (DC-DC) , (AC-DC), PI, Régulateur à hystérésis du courant.

Abstract

Exploiting renewable energy allows the production of decentralized electrical energy, which contributes to a solution for powering an isolated area with the necessary energy. The main objective of this work is to control a wind energy system based on a DC machine driven by a variable speed wind turbine which is connected to the grid and powering a mechanical load. Each component of the wind system is modelled. The DC aero generator is connected to the electrical network through two series converters (DC-DC) and (DC-AC). In fact, the control by a classic regulator (PI) of the speed of the DC generator allowed us to capture the maximum power of the wind and establish the MPPT operating mode. In the same manner, another PI controller is applied to the DC/AC converter in order to regulate the DC link voltage to a smooth value. This wind system supplies a mechanical load whose speed is controlled by using a PI controller applied to a DC/DC converter.

Key words: Wind energy conversion system, H-Bridge, Inverter, Maximum power point, PWM, (DC-DC), (AC-DC), PI, Hysteresis current controller.

Acknowledgements

My thanks go in the first place to Allah the Almighty for the will, the health, and the patience that he gave during all these long years.

Allow us here to express our gratitude to those who helped us to complete this MASTER's memory.

First of all, we would like to particularly thank Pr. BOUTOUBAT MOHAMMED for agreeing to lead this work and for giving us advice and encouragement whenever necessary.

We also thank all the teachers who contributed to our training and the administrators and all the members of the jury who agreed to judge this work.

Finally, we would like to express our gratitude, On the one hand, to our families and friends who welcomed and supported us during this year; on the other hand, to our teachers for their moral support and their logistical support have greatly contributed to the smooth running of this study.

DEDICATIONS

Thank you Allah for giving me the ability to write and think, the strength to believe in it, the patience to go through with the dream and the happiness. We also hope that He will grant us success in all our words and actions.

I dedicate this modest work to the one who gave me life, the symbol of tenderness, who sacrificed herself for my happiness and my success, to my dear mother...

To my father, school of my childhood, who was my shadow during all the years of study, and who watched throughout my life to encourage me, to give me help and to protect me. May God keep them and protect them.

- *All my family.*

- *All friends*

- *To all those I love and who love me.*

- *The entire 2023 electronics class*

TOURBI.Salaheddine

Thank you Allah for giving me the ability to write and think, the strength to believe in it, the patience to go through with the dream and the happiness. We also hope that He will grant us success in all our words and actions.

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- *All my family.*
- *All friends*
- *To all those I love and who love me.*
- *The entire 2023 electronics class*

MEITAR Ahmed

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Notations

V_0: Average value of the slow component;

V_t(t): Fluctuations caused by turbulence;

E_c: Kinetic energy in (joule);

V: Wind speed in ;

m: This is the mass of air ;

ρ: Is the density of air in general it is equal to 1.25 ;

V_{ol}: This is the volume of air that rotates the blades of the wind turbine;

S: This is the area swept by the blades of the wind turbine ;

e: Is the thickness of the blades ;

P: The power in watts ;

E: The energy in joules ;

t: The time in seconds ;

v: This is the speed of the tip of the blades in ;

R: The length of the blades ;

Ω: The angular speed of the blades ;

λ: representing the ratio between the speed of the tip of the blades of the wind turbine and the speed of the wind;

Cp: power coefficient;

Pm: The power extracted by the rotor ;

mt: Is the mass per second ;

V_1: The speed before passing through the rotor plane ;

V_2: The speed after passing through the rotor plane in (m/s) ;

Ω_r: speed of the generator (fast shaft in rad/s);

G: multiplication ratio;

Ω_t: Blade rotation speed

J: Total inertia of rotating parts ;

f: Coefficient of viscous friction;

Cem: Electromagnetic torque of the generator ;

I: current consumed by the motor;

U: Motor supply voltage E: electromotive force;

R: internal resistance of the winding;

p: Number of pairs of poles of the inductor;

a: Number of armature winding path pairs ;

N: Total number of active armature leads;

ϕ: Useful flux per pole ;

Ω: Rotation speed ;

Ea: Counter-electromotive force;

Pem: the electromagnetic power ;

Pu : the useful power ;

Pje: joule losses at the inductor ;

Pj: joule losses at the ;

Pfer: ferromagnetic losses;

Pmeca: mechanical losses;

E: the f.e.m.;

I: the armature current ;

Tem: the electromagnetic torque ;

Tu: the useful torque ;

R: the armature resistance;

r: the inductor resistance;

Cr: It is the resistant torque imposed by the load;

J: The total moment of inertia (machine + driven load);

f: The friction proportional to the speed of rotation;

GSC: Grid side converter;

MSC: Machin side converter.

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GENERAL INTRODUCTION

GENERAL INTRODUCTION

Wind energy is one of the oldest used energy sources. Its use in the past was widespread in the production of mechanical energy as man tried to use the wind in his life and benefit from it. Moreover, the wind is used in many ways for example; move sailing boats, rotate windmills to get water from the ground, etc **[1].**

The wind turbine first appeared as a windmill with a horizontal axis of mechanical power generation, used since 1000 AD in Persia, Tibet and China. The transfer of the mechanical mill from the Middle East to Europe between 1100 and 1300, wind-generated electrical energy is sometimes considered the most important promising renewable energies should be developed to replace hydrocarbons. But due to the volatile nature of the wind, wind energy can only be considered as a complementary source of energy and not an alternative to traditional solutions.

At the moment, many countries are resolutely moving towards wind energy. During the 19th century tens of thousands of modern windmills with rotors with a diameter of 25 meters were put into operation in France.

Currently, China tops the list of countries producing this energy with 145,362 MW, which is about 33% of the global production of this energy, followed by the United States with a production of 74,471 MW, Germany with 44,947 MW, India with about 25,088 MW and Spain with 23,025 MW.

As for Algeria, we are still in an initial stage with one experimental wind farm with a nominal capacity of 10 MW, knowing that the average annual wind speed is between 2 and 6 m/s. But modern turbines are more reliable and efficient, and their noise has been significantly reduced compared to their predecessors. The current pursuit is in the development of new control strategies to maximize the collection of energy from turbines.

Therefore, researchers working in the field of renewable energies are diligently pursuing research and development with the aim of improving the efficiency of electromechanical conversion and the quality of energy supplied to the grid. In this context, the report below describes a study on the use of direct current machines in a wind system supplying an electrical network.

The work presented in this thesis simulating a wind system powering a mechanical load and inject the surplus power in the grig, and extract the needed power from the grid when the system does not produce enough power, our work consists around 3 main chapters which are briefly described below:

In the first chapter of this thesis, state of the art wind power will be presented.

This is a fairly detailed study of the wind system and the various structures present. Next, we discuss the different types of generators used in the conversion chain and the different possible architectures.

The second chapter is devoted to the detailed modeling of the different systems that make up the wind system, namely: the turbine, the DC machine, the chopper, and the three-phase inverter.

The third chapter is devoted to the development of the different control strategies applied to the different inverters (chopper and inverter) to operate the wind system in MPPT and extract the maximum energy from the wind and powering a DC mechanical load connected to the DC link. It will feed the machine while injecting the surplus into the electrical network or feeding the load in the event that the turbine does not produce enough energy.

Finally, we close this thesis with a general conclusion about the work done and will offer some points of view to give fruitful follow-up to this work in the future.

Chapter 1: ***State of the art on wind turbine systems***

1.1 Introduction

The wind is one of the clean renewable energy. It is a flow of gases and it is caused by the differences in the atmospheric pressure. When a difference in the atmospheric pressure happens, the air moves from higher into lower pressure areas. However, all of these caused by sun effects, because the sun heats the wind unequally around the earth and 1 to 2 percent of the solar energy which reaches the earth is stocked in wind. The human tried to use the wind in his life and get advantages of it. Furthermore, the wind is used in several ways for example; moving sailing boats rotate windmills to get water from underground, etc. The wind can be in general divided into two types, global and local. However, the global wind is the large movements around the world and the local is the movements of wind in a specific part on earth. The wind can be described by two main factors speed and direction, and controlled by a combination of three forces which are: - Pressure gradient force (PGF). - Coriolis force. - Friction. The wind can be warm or cold because of the earth's surface effects in both friction and pressure of the wind, and the warm wind has less density than the cold. Oceans give a smoother surface more than the land and drastically different certain heat that cause ocean or land breezes through changing of air pressure. In the daytime the heating is increased more over the oceans, so the air over the land goes up and wind speed goes fast from ocean to land and in the opposite direction at night **[1].**

1.2 Background

With the use of oil and gas in the production of electric power which pollute then vironment, the researchers started to find sources that can be used in producing electric power without any dangerous impact on the environment. The air is made of several gas particles and these particles moves quickly during windy days and that produce a movement energy called kinetic force E_k caused duo to the wind motion. The first scientist who figured out this energy is Robert Boyle in 1660, then it has been developed theoretically by Daniel Bernoulli in 1738. After that, the scientists tried to develop it more and more. The Kinetic energy can be obtained by:

$$E_k = \frac{1}{2} m v^2 \tag{I. 1}$$

where $v$is the speed of wind in meter per second (m/s), and $m$is the mass of wind in kilogram (kg) and known as the body of air with specific characteristics (temperature, humidity and pressure) and is given as:

$$m = 3\frac{KT}{v^2} \tag{I. 2}$$

Where k is a constant and equal to $1.38 * 10^{-23}$ (J/kg) and T is the air temperature of gas in Kelvin.

1.3 Wind turbine

A wind turbine is a rotating machine which converts the wind kinetic energy into mechanical energy. If the produced mechanical energy is then converted to electricity, the system is called ~~a~~ wind generator Based on the axis in which the turbine rotates wind turbines can be separated into two types (Horizontal Axis Wind Turbines and Vertical Axis Wind Turbines). The first kind are more commonly used due to several inherent advantages, but, the latter being used in small scale **[2]**.

1.4 History of Wind Energy

The idea of using the wind as an energy started by moving the boats along the Nile River in early time by 5000 B.C, while the first simple windmills were used in china in pumping water 200 B.C, however, Persia and the Middle East used the vertical axis windmills with woven reed sails for grinding the grain. Holland was best known for development in windmills design, by 14th century, which preformed many helpful functions in that time, Including timber milling and the most important function was pumping water to drain marshy, low areas and reclaim large lands of Netherlands farming. At the end of 18th century, about 10,000 wind turbines were used in Netherland and Britain as well. By 1990 in Denmark there were about 2500 windmills for mechanical loads which were producing an estimated combined power approximately to 30MW. The wind turbine technology is one of the attractive renewable energy. The wind power is developed significantly in 1990, where more than 10,000 megawatt of the wind power capacity used around the world. The total amount of the Swedish electricity production in 2003 was 143 terawatt hours, the important part comes from hydropower and nuclear power, which participate about 65 terawatt hours each. 11 terawatt hours come from steam power. The total amount of installed wind power was approximately 400MW at the end of 2003. The wind power has been the fastest-growing exporter of the renewable energy around the world in the last years, and ability is also progressively expanding in Sweden. Since 2000, the Swedish production has grown from 0.5 to 7.1 terawatt hours in 2011, there were approximately 2000 wind turbines in Sweden **[1].**

1.5 Main components of wind turbine

Wind turbine with gearbox (structure shown in Figure 1.1) and directive-drive wind turbine (structure shown in Figure 1.2) share the commercial wind power market. The latter is also called gearless wind turbine whose rotor is directly connected with a permanent magnet generator. The main components of wind turbine are listed as follows **[1]**:

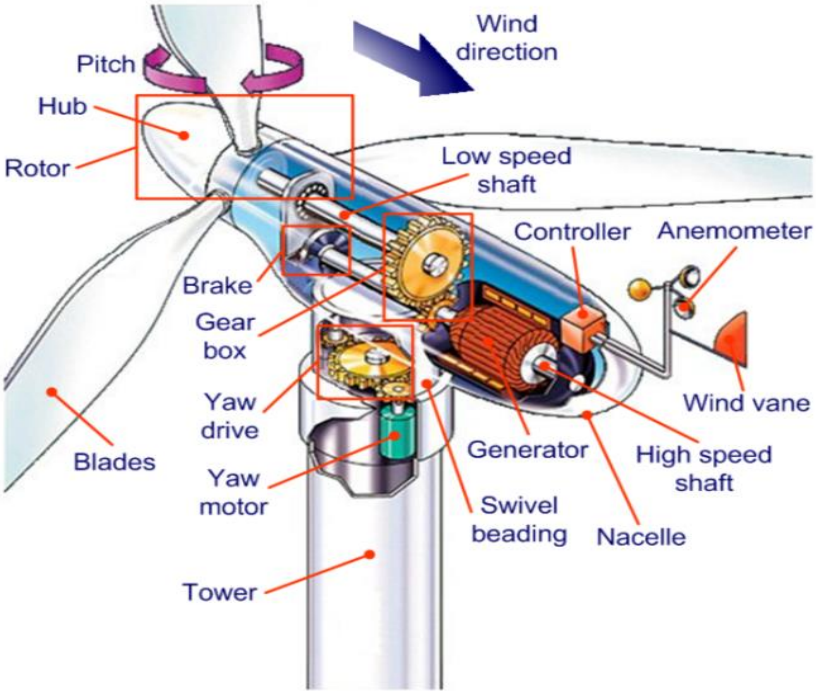

Figure I- 1: Structure of wind turbine with gearbox**[3]**.

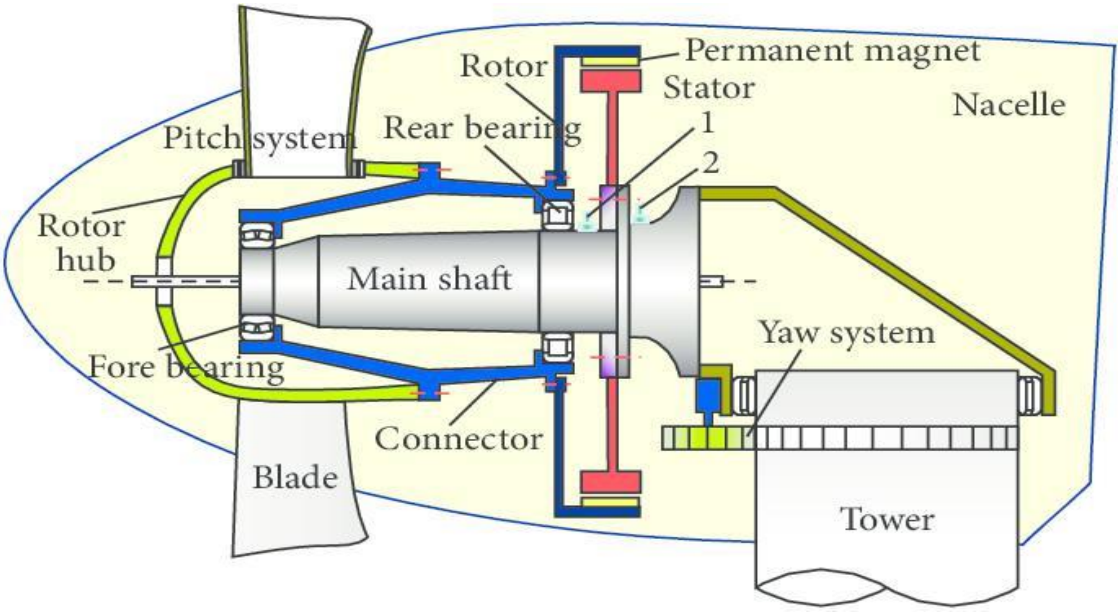

Figure I- 2: Structure of directive wind turbine **[4]**.

1.5.1 Rotor

It is the heart of a wind turbine which contains the blades and the hub. Blades are used to capture the wind energy and convert it into mechanical energy to force the rotor to rotate. Hub is used to support the blades and is connected to other parts of the wind turbine

1.5.2 Pitch system

Pitch system turns the blades in/out of the wind to keep the rotor rotating in a lager wind speed range. It is also an important power adjustment system for variable speed wind turbine. It limits the power generation at the rated output power and helps wind turbine to catch as much as possible wind energy when wind speed is low. It consists of a control system and actuators.

1.5.3 Hub

The hub is the component holds the transmits motion and the rotor together to nacelle and it transmits the loads that which are generated by the blades, most of the hubs are made of steel either cast or welded and there are three main types of them that have been applied in HAWTs.

a. **Rigid Hub**: it is designed to keep all main parts in a stable position relative to the main shaft, they are the most used design and are roughly universal for machines with three or more blades

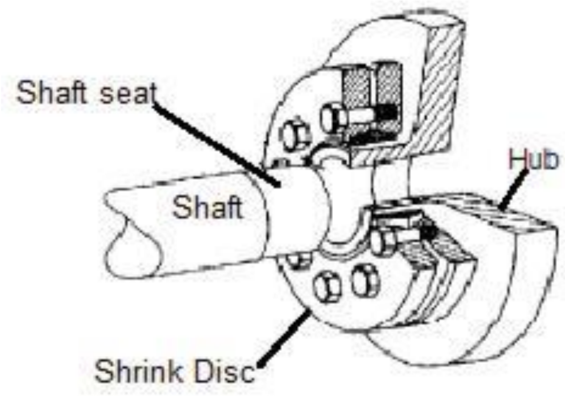

Figure I- 3:Rigid Hub **[5].**

b. **Teetering Hub**: this type of hubs are used on roughly all two blades of the wind turbines. The teetering hub can decrease loads due to imbalances of aerodynamic or effects of dynamic from rotation of the rotor or yawing of the wind turbine.

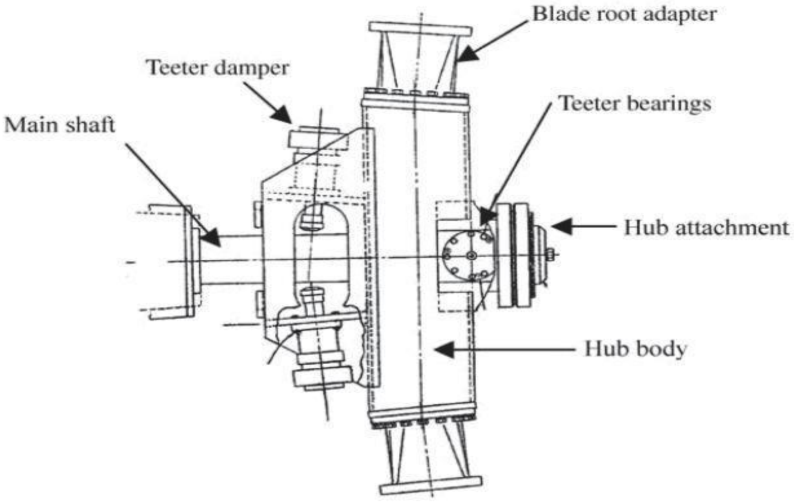

Figure I- 4 : Teetering Hub **[5].**

c. **Hinged Hub**: This type of hubs are basically a rigid hub with hinges for the blades, this hub in some ways a cross between a teetering hub and a rigid hub also the main function of the coupling is to transmit torque between two shafts, but it may have another function too.

1.5.4 Wind speed sensors

Generally, two wind speed sensors are installed in wind turbines:

An anemometer for assessing direction and an anemometer for measuring speed usually located at the back of the nacelle. The electronic signals emitted from the anemometer are used by the wind turbine driving control system to start the wind turbine when the wind speed reaches approximately the mean value of:5 m/s. Also, the electronic control system automatically stops the wind turbine if the wind speed is over 25m/s to ensure wind turbine system protection. The drive control system uses the signals from the wind vane to direct the wind turbine into the wind using the steering gear.

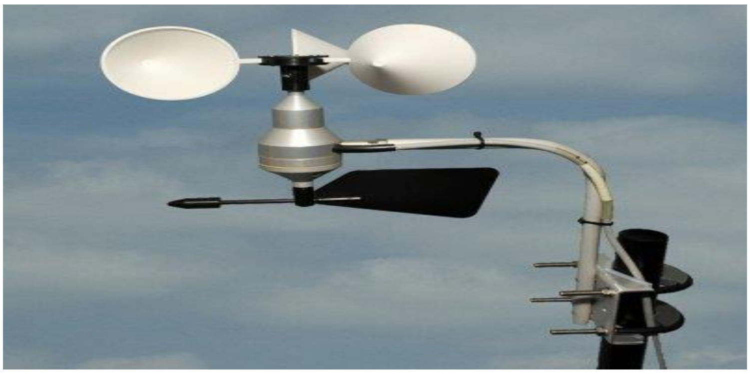

Figure I- 5 : Wind speed sensors.

1.5.5 Generator

Generally, two kinds of generators are used:

a. Direct current generator;

b. Alternative current generator.

Anyway, it converts the mechanical energy that the rotor sends to it, into electrical energy which can be injected in the grid.

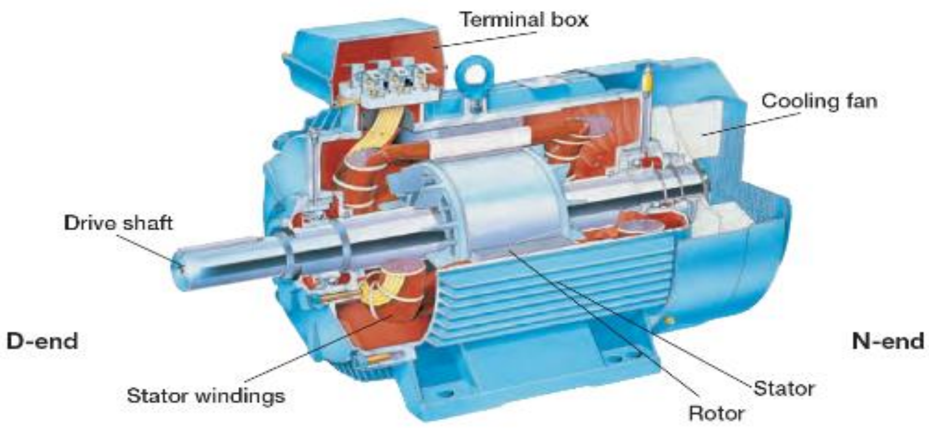

Figure I- 6 : Scheme of the generator **[5].**

1.5.6 Nacelle

It is the housing that protect sall components which is attached to it and the prime frame as well, this enclosure is in particular importance for the electric systems of the wind. However, the nacelle which sits at the top of the tower and is connected to the rotor which consists of the main components of the wind turbine, such as the gearbox, main frame and generator. The nacelle is made of fiber glass and protects the internal components from the environment. The cover of nacelle is fastened to the main frame, which supports all the other parts inside the nacelle, the main frames are large metal structures that must be able to withstand the large fatigue loads.

1.5.7 Blades

These are aerodynamically designed structures such that when wind flows over them they are lifted as in airplane wings. The blades are also slightly controlled for greater aerodynamic efficiency.

1.5.8 Brake

This is either a mechanical, electrical or hydraulic brake used for stopping the turbine in high wind conditions or any dangerous cases.

1.5.9 High-speed shaft

The main role of the high speed shaft is to transmit the speed and torque from the gearbox and drives the generator to produce electric power.

1.5.10 Low-speed shaft

It is the principal – rotating element which ~~is~~ transfers torque from the rotor into the rest of drive train which ~~is~~ transfers power from the rotor to the generator. Moreover, it supports the rotor weight, and it is connected to the gearbox to increase the rotation speed.

1.5.11 Yaw system

Yaw system makes the rotor face into the wind when the wind direction changes. It consists of a control system and actuators.

1.5.12 Gearbox

The gearbox steps up the speed according to the electric generator requirement. However, gears connected the low speed shaft to the high speed shaft and the rotational speeds increased from about 30 to 60 rotation per minute (rpm) to about 1000 to 1800 rpm, the rotational speed is required by most of generators to produce electricity.

1.5.13 Controller

This is the most important part of the turbine as it controls everything from power output to pitch angle. The controller senses wind speed, wind direction, shaft speed and torque at one or more points. Also the temp of generator and power output produced is sensed

1.5.14 Wind direction

Generally erratic in nature, hence the rotor is made to face into the wind by means of control systems.

1.5.15 Wind vane

Basically the job of a wind sensor, measuring the wind speed and communicating the same to the yaw drive, so as to turn the turbine into the wind flow direction.

1.5.16 Anemometer

It is applied to measure the wind speed and sends it to SCADA which is incorporated in the wind system.

1.5.17 Tower

Due to surface aerodynamic dray caused by land or water surface, wind velocities increase at higher altitudes. The tower helps the nacelle to stand at a high altitude so that improving the power generation of wind turbine.

1.6 Wind turbine operation

The operation of wind turbine is automatically controlled according to the wind conditions. A normal wind turbine operation procedure is as follows **[6]**:

1.6.1 System test

The rotor position is checked and changed if necessary, the system is checked for faults. If no irregularities cases are detected, the wind turbine is ready for operation.

1.6.2 Idling

The wind turbine stands with braked rotor and is turned into the wind inflow direction by the yaw system. With the wind speed measurement data providing by the anemometer, the system determines when the starting level wind speed has been reached **[6]**.

1.6.3 Initiation

The rotor blades are pitched into the wind, and the mechanical rotor brake is released. The rotor starts to rotate.

1.6.4 Powering up

The rotor speed increases until the synchronization speed of the generator is reached. If the synchronization speed can be maintained constant over a specified period, the generator is then coupled to the grid **[6].**

1.6.5 Power generation

If the generator has successfully started the operation, power is delivered to the power grid through the generator.

1.6.6 Power off

If the wind speed is too strong and exceeds the cut-out wind speed, the system is completely stopped by using of the mechanical brake.

1.7 Wind turbine development tendency

The initial wind turbines were passive stall-regulated load control, working in a narrow wind speed range. Paul La Cour designed the first wind turbine for the direct current production in 1891. After the First World War, due to the experience of propeller design for aircraft, the scientific understanding of wind turbine design greatly stepped forward in Europe. With the new theoretical background of wind turbine, many promising methods for the modern wind turbine design emerged. The wind turbine WIME D-30 with a diameter of 30 m and a power of 100 kW operated from 1931 to 1942 in Crimea and produced power into a small 20 MW grid. However, the start of the Second World War ruined these models. With the reconstruction of Europe after the war, the developments of wind turbine attracted again the researchers. Some prototypes of wind turbine were fabricated and provided electricity to the grid. Such as the famous Gedser wind turbine, TVIND wind turbine , respectively. After 1980, the renaissance of the wind energy started tremendously in Europe and the USA. After almost 40 years, wind turbine shares a part of the electricity market. It is necessary to summarise the evolutions about site, size, power, and control of wind turbine so that the research background of this thesis can be unfolded **[6].**

1.7.1 Evolution of site

In order to catch as much as possible wind energy, onshore wind turbines are being installed in remote locations with abundant wind resource. Nowadays, offshore wind power has successfully attracted interest in some countries, such as Denmark, China, UK, Netherlands and Germany, because of its excellent wind resource and the avoidance of land-use issues. With the development of support technologies, wind turbines are being erected from shallow water (for fixed foundation wind turbine) to deeper water (for floating wind turbine)**.**

1.7.2 Evolution of size

If the aircraft Airbus A380 with a 79.75 m wingspan is regarded as a giant, commercial wind turbines in our days should be called super-giant, as their rotor’s diameters easily exceed 100 m. Referring to the modern wind turbine fabricated after the year 2004 shown in Figure I.7

Figure I- 7 : Gedser wind turbine, 200 kW, D = 24 m, Denmark 1957**[6].**

their total heights are at least 150 m. The wind power through an area A at a velocity *v* is given by:

$$P = \frac{1}{2}\rho A v^3 \tag{I.3}$$

where, ρ is the air density. As can be seen from (I.3), the power (P) is proportional to the cross-sectional area A. Hence, improving the area of rotor is an efficient way to capture much more energy with the same wind speed *v*. The rotor diameter of the newest Siemens offshore wind turbine SG 10.0-193DD is 193 m .Nowadays, the size limit of a wind turbine is unknown. With the ambition for capturing enormous energy, larger wind turbine may appear in the future.

1.7.3 Evolution of rated power

According to Yang et al. wind turbines are becoming larger with higher rated power, as shown in Table.

Manufacturer	Wind turbine model	Rated power
Repower	M104	3.4 MW
GE	4.0-110	4.0MW
Gamesa	G-128	4.5MW
Enercon	E-126	7MW
Wind Power Ltd	Aerogenerator X	10MW (in development)

Table I- 1: Evolution of wind turbine rated power **[6].**

1.7.4 Evolution of control

In the beginning, wind turbines were based on passive stall-regulated load control, fixed-rotational speed, working in a narrow wind speed range. Then, variable speed wind turbine with active pitch control appeared in order to produce the maximum power. The application of blade-pitch control has allowed modern wind turbines to be larger and capable of operating over wider wind speed ranges. However, researchers are trying to develop intelligent blade that can measure wind speed and automatically adapt itself to wind conditions. It is believed that with the intelligent blades, the reliability and efficiency of wind turbine can be enhanced.

1.7.5 Evolution of cumulative installed capacity

According to the report of Wind EUROPE .the total cumulative installed capacity in Europe has reached 204 GW in 2020, as shown in Figure 1-8. Therefore, wind turbines are giant machines that automatically operate at remote places or off-shore under harsh and random environment without a human supervisor. As a costly power generator and with increasing contribution to grid, the reliability of wind turbine is an important issue. However, its operation environment, the location of site and size of wind turbine bring a lot of challenges to reliability and maintenance of wind turbine:

1.7.6 Challenges caused by site

The remote site of wind farm may not be accessible at all the time. Hence, the maintenance activities for wind turbine only can be carried out during an accessible time period. It requires prediction and planning. The deteriorated components that is likely to fail during the inaccessible time period need to be repaired / replaced in advance to avoid undesirable downtime of the system.

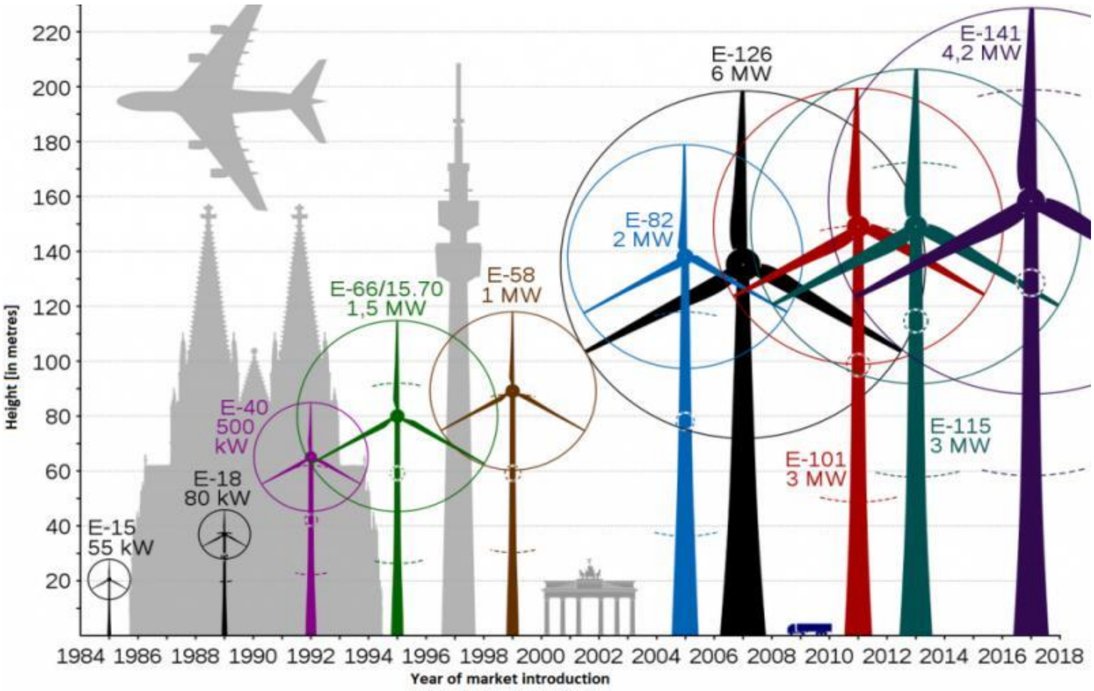

Figure I- 8 : Evolution of wind turbine size and power**[7].**

1.7.7 Challenges caused by size

To carry out maintenance activities, the increasing size of wind turbine may need special vehicles or equipments. Besides, the rapid growth in design size that lacks a practical operational experience may cause unexpected failures.

1.7.8 Challenges caused by control system

The control systems used for pitch, generator and converter are more and more sophisticated. However, the electrical and electronic components are showing that they are less reliable than mechanical components. Furthermore, the existing condition monitoring system is not effective for detecting electrical and electronic failures. The downtime caused by electrical and electronic components failures are more significant in remote location and offshore because of the reduced accessibility.

To improve the reliability of wind turbines, several methods can be considered:

a. Improving wind turbines design theory and magnification technology;

b. Developing advanced condition monitoring system for wind turbine;

c. Producting the remaining useful life of the wind turbine and providing economical maintenance schedules for wind turbine in service.

1.8 Classification of Wind turbines

Generally, turbines are divided into two types according to their axis of rotation.

1.8.1 Vertical axes turbine

This type of wind turbine is characterized by its vertical axis. It uses the principle of operation omnidirectional, which has the advantage of capturing the winds wherever they come from without the need for a referral mechanism. Another advantage of this type of wind turbine is the size of the blades, which is not so constraining compared with that of the horizontal axis type. Several models of vertical-axis wind turbines have been designed, but the two most famous are those of Darrieus and Savonius. All models in this category have remained at the prototype stage, as they are currently not profitable, but all show ingenuity.

1.8.1.1 Darrieus Wind Turbine

The Darrieus wind turbine is a wind turbine based on an H-shaped rotor, cylindrical or helical, which rotates around a fixed rod. This type of vertical wind turbine has many advantages, including being able to be installed in much ventilated places and being very quiet compared to other wind turbines on the market. The disadvantage of this type of wind turbine is that it needs a relatively strong wind to start rotating and therefore to produce energy.

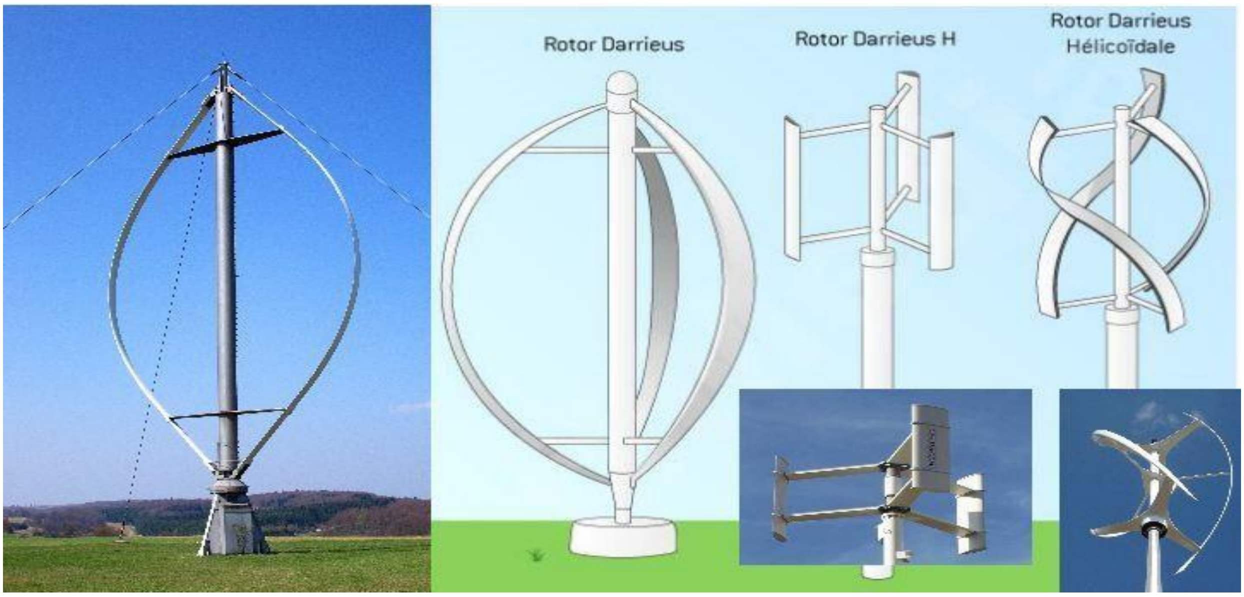

Figure I- 9 : Darrieus wind turbine**[8]**.

1.8.1.2 Savonius wind Turbine

This type of wind turbine has the advantage of being particularly easy to install because it is not cumbersome. The principle is that two half-cylinders rotate, driving one and the other, even with a very light wind. In addition to a very attractive design aesthetic that allows installers to easily project themselves with this wind turbine, the Savonius wind turbine can work well with very low winds, which is not the case with the Darrieus wind turbine.

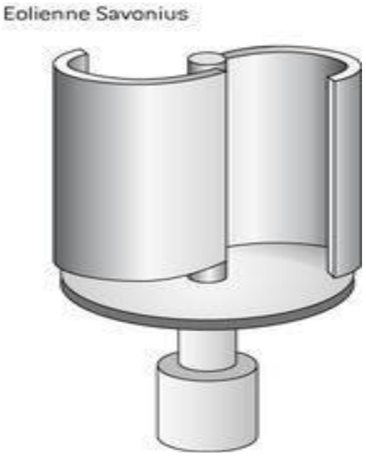

Figure I- 11 : Scheme of the Savonius rotor **[8].**

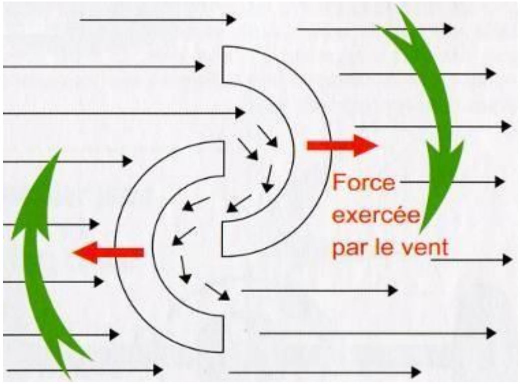

Figure I- 10 : Scheme of the Savonius rotor principle **[8].**

1.9 Horizontal axes turbine

1.9.1 Horizontal-axis wind turbines

They are the most commonly used type of wind turbine. They can be defined as a turbine in which the shaft of the rotor is in the direction of the wind. A wind turbine could be single-bladed, double-bladed, or three-bladed. The blades are aerodynamically designed to rotate with the aerodynamic lift of the force. The pressure difference is created between the upward and lower faces of the turbine blades. The speed of air through the front side of the blade is high, and a low-pressure area is created there. On the other hand, airspeed is low on the rear side, and a high-pressure area is created there. The air from the high-pressure region moves the blades upward, giving them an aerodynamic lift. This relation is called Bernoulli's relation, which states that where the pressure is high, speed will be low for a fluid. The blades of the turbine are connected to the rotor of the electrical generator. HAWT can capture stronger winds and have greater efficiency.

1.9.1.1 Horizontal axis wind turbines with Aval direction

The wind blows on the back of the blades from the nacelle. The rotor is flexible and self-steering. The upstream turbine arrangement is the most common because it is simpler and gives the best results for high powers. There is no rudder, the maneuvering efforts are less important, and there is better stability. The blades of horizontal-axis wind turbines must always be oriented in the direction of the wind. For this, there are orientation devices on the nacelle according to this direction **[8].** (Figure 1-12)

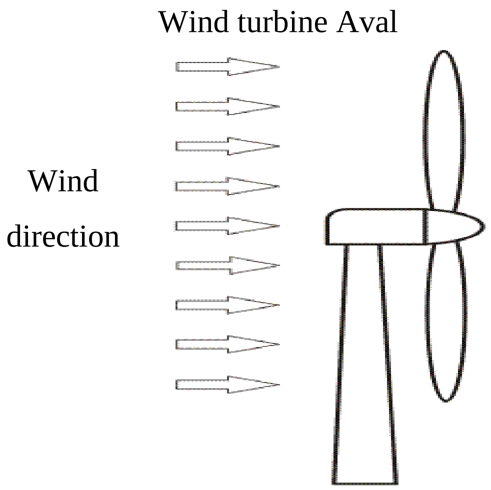

Figure I- 12 : Wind turbine Aval.

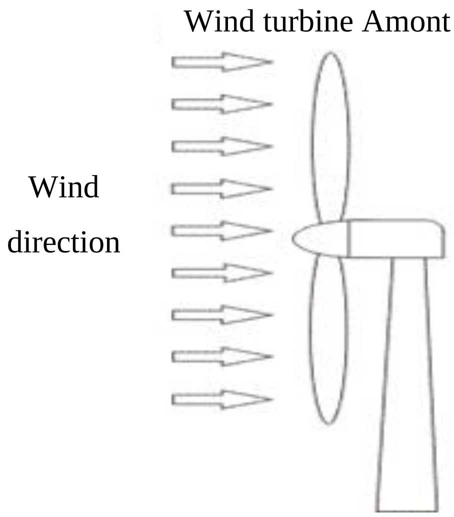

Figure I- 13 : Wind turbines Amont.

1.9.1.2 Horizontal axis wind turbines with amont direction

The wind blows on the front of the blades in the direction of the nacelle. The blades are rigid, and the rotor is oriented according to the direction of the wind by an orientation device **[1]**.(Figure 1-13)

1.9.2 Effect of number of blades

When the number of blades on a wind turbine increases, the aerodynamic efficiency increases. However, as we move from two blades to three blades, we get an increase in efficiency of 3%, but as we move from three blades to four blades, the efficiency gain is marginal. Moreover, as we increase the number of blades, the cost of the system increases. When we use a larger number of blades, the blades should be thinner to become more aerodynamically efficient. But when the blade has a thinner portion at the root, it may not resist bending stress induced by axial wind loads. In general, wind turbines with three blades and a thicker root are used. In general, the lower the number of blades on a wind turbine, the lower the cost of materials and manufacturing **[8]:**

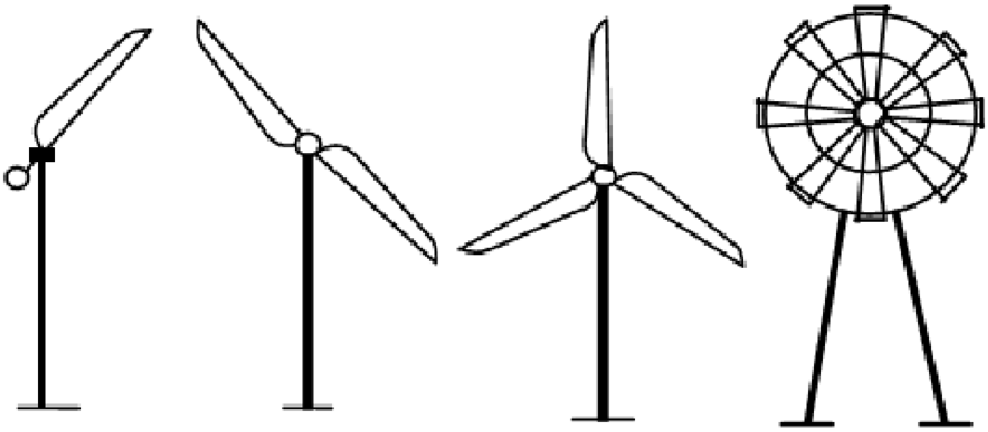

Figure I- 14: Horizontal wind turbine blades.

1.10 Different wind turbine technologies

There are basically two wind turbine technologies, those with fixed speed and those with variable speed

1.10.1 Fixed-Speed Wind Turbine

A fixed-speed wind turbine system is a simpler way of connecting wind power onto the electric grid. Today, such a system uses an induction machine almost exclusively for converting the mechanic power extracted from wind into electric power. The induction machine’s operational characteristics, together with its rather low price and robustness, are the main reasons for this. The stall and the pitch aerodynamic control strategies presented in the preceding sections have been used in combination with a fixed-speed system **[9].**

1.10.2 Variable-Speed Wind Turbines

The fault response of variable-speed systems is, to a large extent, influenced by the power electronic converter. A modern power electronic converter can theoretically maintain the desired output current almost regardless of the grid voltage, provided that the current and voltage limits of the converter are not violated, and that driving energy from the wind turbine is available [9].

1.11 Design of the wind turbine rotor

There are several parameters involved in the design of an efficient yet economical wind turbine. Generally and efficient design of the blade is known to maximize the lift and minimize the drag on the blade. Now, minimization of the drag means that the aerofoil should face the relative wind in such a way that minimum possible area is exposed to the drag force of the wind. Furthermore the angle of this relative wind to the blades is determined by the relative magnitudes of the wind speed and the blade velocity. The thing to note here is that the wind velocity basically stays constant throughout the swept area but the blade velocity increases from the inner edge to the tip. Which means the relative angle of the wind with respect to the blade is ever-changing **[2]**.

1.12 Different stages of energy conversion

Wind generators can be grouped into different categories. They can be classified according to:

a. The nature of the electromechanical converter (synchronous, asynchronous machine, direct current, etc.).

b. The nature of the mechanical coupling (presence of speed multiplier or direct attack).

c. The type of operation (fixed or variable speed).

d. The type of sensor (vertical or horizontal axis).

These different categories can intersect, for example, a wind turbine can be variable speed, have a speed multiplier and an asynchronous generator **[8]:**

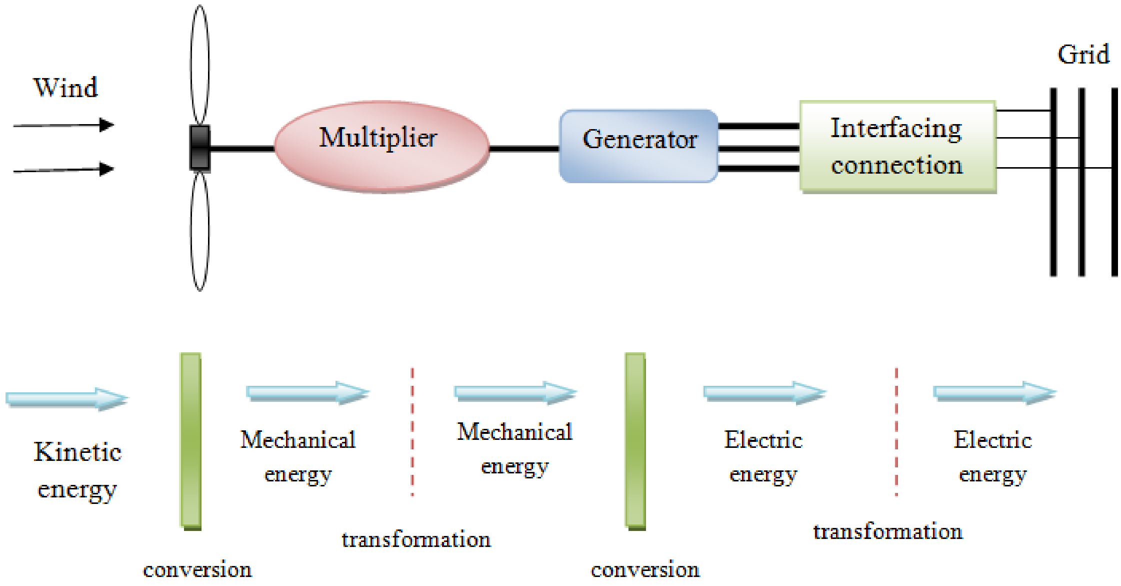

Figure I- 15 : Different stages of energy conversion **[10].**

1.13 Speed multiplier

The mechanical transmission is done by means of a multiplier of speed whose main role is to adapt the speed of rotation of the turbine to that of the generator. It helps turn high-torque, slow-speed power into a low torque power and fast speed. The multiplier therefore connects the (primary) speed of the wind turbine to the (secondary) shaft of the electrical generator. The principle of wind power conversion is illustrated in the figure. The whole chain of conversion involves a wide variety of fields and poses aerodynamic problems, mechanical, electrical or automatic **[11]:**

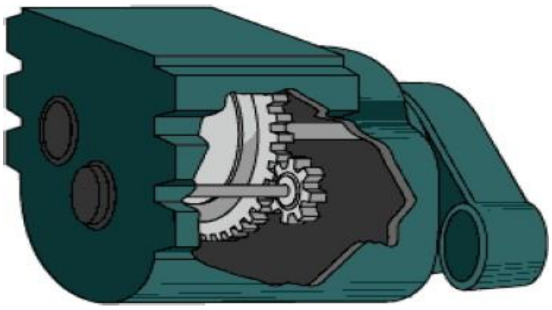

Figure I- 16:Speed multiplier.

1.14 Variable speed systems

1.14.1 Wound rotor induction machine

This machine requires the use of a gearbox, on the other hand its robustness is slightly reduced by the presence of the ring and brush system. The asynchronous machine has a wound rotor with electronic adjustment which ensures the variation of the slip. This allows the assembly to operate at variable speed over a greater speed range compared to the squirrel-cage induction machine.

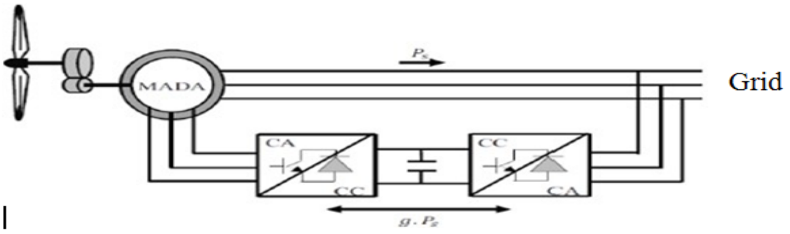

Figure I- 17 : Wound rotor induction machine **[12].**

1.14.2 DC-Excited synchronous machine

The synchronous machine has not been widely used in wind power installations, such as the case of an asynchronous machine, because it is more complex to control and it requires a constant speed at the rotor to create a constant frequency voltage at the stator.

Another solution is proposed to operate the synchronous machine at variable speed. It consists of using an inverter-rectifier assembly.

The speed variation range is from 0.5 up to 1.2 of the speed of synchronism. But, contrary to the cases of the asynchronous generator with Double Power supply, the conversion chain placed on the stator must be sized for the full power of the production system.

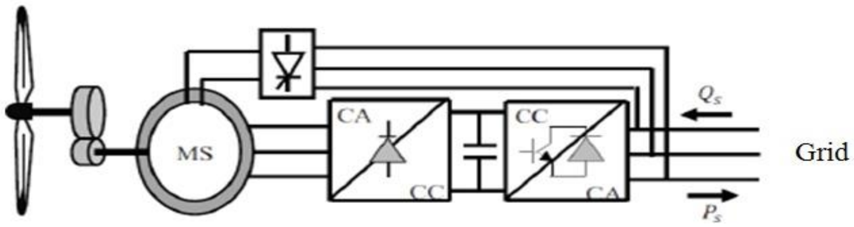

Figure I- 18 : Synchronous machine connected to the network via a converter.

1.14.3 Permanent magnet synchronous machine

The Permanent Magnet Synchronous Motor (PMSM) is an AC synchronous motor whose field excitation is provided by permanent magnets, and has a sinusoidal back EMF waveform. The PMSM is a cross between an induction motor and brushless DC motor.

This type of machine uses a multi-pole rotor permanent magnet, which gives the advantage of developing a very high mass torque and eliminating the gearbox. In addition, the machine does not consume reactive energy in the circuit rotoric. The speed variation range is from 0.6 up to 1.2 of the speed of synchronism

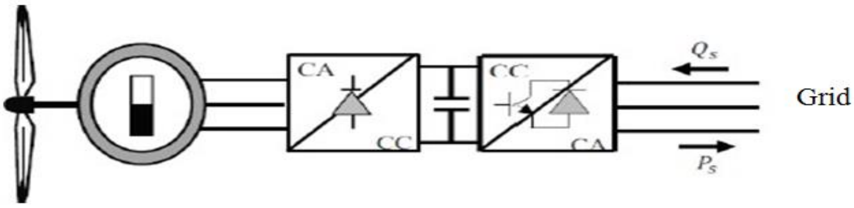

Figure I- 19 :Permanent magnet synchronous machine**[12].**

1.14.4 DC machines

DC motors make up most of the mechanical motion we see around us. They convert electrical energy in the form of direct current into mechanical energy. Due to its simple operation and controls and due to its availability in a wide range of power ratings, it was chosen to simulate the wind in the wind turbine system. We will focus on DC motors and their use as generators in wind systemsin the next chapter**:**.

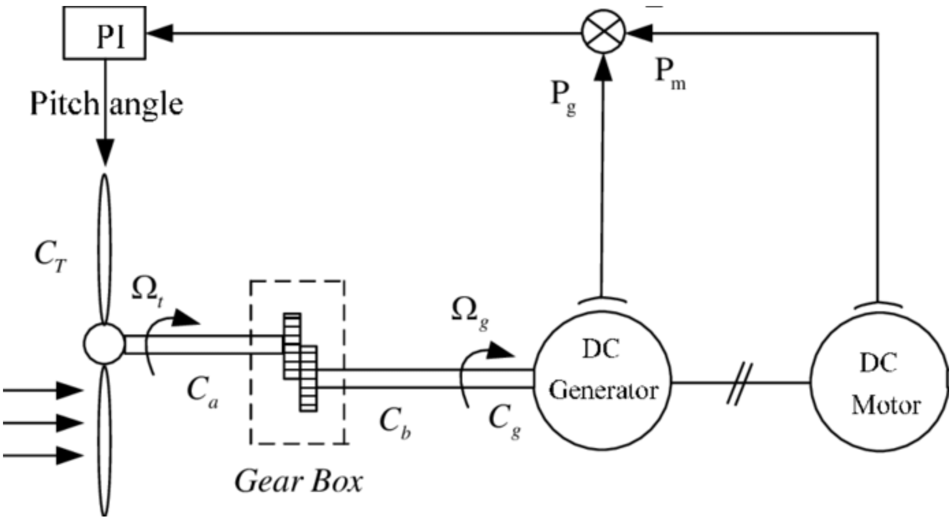

Figure I- 20 :DC-machine**[13].**

1.15 Conclusion

In this chapter, some main notions on wind technology were given concerning mainly, its types of its classification, its main constituents and its operating principle of a wind turbine chain, the different types of machines used characterizing their operating principles..Through the literature, any wind energy system structure based on DC generator has been studied yet. So, in this thesis, we propose the study and the control of a grid connected wind system based on a DC generator and powering a mechanical load composed also of a DC machine. Hence, the next chapter is reserved to the proposed wind system modelling.

Chapter 2: Wind Energy system modeling

2.1 Introduction

After a brief description of the most used wind turbine system structures in the previous chapter, the main goal of this present chapter is the system components modelling. In fact, the studied system is composed by:

1- Wind turbine;

2- DC generator;

3- H-Bridge;

4-Inveter;

5-Continuous bus.

2.2 Wind system modelling

The general scheme of the studied system is depicted in Figure (II.1). All its components are described hereafter:

2.2.1 Wind speed

Since wind is the source of electrical energy produced by wind turbines, The most important problem is t the amount of wind which cannot controlled and therefore the lack of control over the energy produced. The wind speed *V (t)* can be divided into two components as follows [12]:

$$V(t) = V_0 + V_t(t) \qquad \text{(II. 1)}$$

V_0 : Average value of the slow component;

$V_t(t)$: Fluctuations caused by turbulence.

The proposed wind energy conversion system is presented in Figure(II-1).

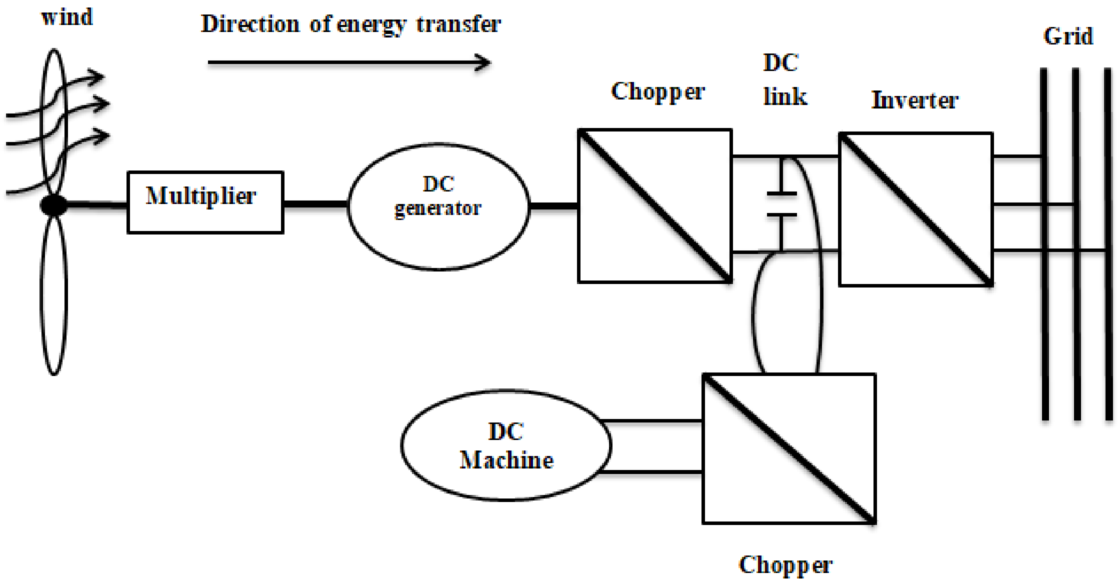

Figure II- 1 : Electrical scheme of the proposed wind system.

2.2.2 Turbine modelling

The power extracted by a wind turbine is given by the following relationship:

$$P_{win} = \frac{1}{2} . C_P(\lambda,\beta).\rho.S.V_w^3 \qquad \text{(II. 2)}$$

Where λ is defined by:

$$\lambda = (\Omega t \cdot R)/v \qquad \text{(II. 3)}$$

C_P: Power coefficient;

λ: Specific speed;

β : pitch angle;

ρ: The wind density in [Kg/m3];

S: The area swept by the blades of the wind turbine [m^2];

Ω_t: The angular mechanical speed of the wind turbine rotor [rad/s];

V_w: Wind speed [m/s];

R: Radius of a turbine blade [m].

In our case the gearbox considered as sample gain (G). So, one can write

$$\Omega_{mec} = G.\Omega_t \qquad \text{(II. 4)}$$

Ω_t: is the DC generator speed (rad/s) ;

G: Gearbox gain;

Ωt : Turbine speed (rad/s).

So, the generator torque (C_g) is related to the turbine torque (C_t) by:

$$C_g = \frac{1}{G} C_t \qquad \text{(II. 5)}$$

The mechanical equation of the wind system at the generator side is expressed by:

$$J \frac{d\Omega_{mec}}{dt} = C_g - C_{em} - f\Omega_{mec} \qquad \text{(II. 6)}$$

Where, J and f are given respectively given by:

$$J = \frac{J_{tur}}{G^2} + J_{mach} \qquad \text{(II. 7)}$$

$$f = \frac{f_{tur}}{G^2} + f_{mach} \qquad \text{(II. 8)}$$

J_{tur} *(Kg.m^2)* is the turbine Inertia; J_{mach}*(Kg.m^2)* is the generator inertia; f_{tur}(N.m.s) is the turbine friction; f_{mach}(N.m.s) is the generator friction.

C_{em} is the electromagnetic torque of the generator (N.m).

From these previous equations, one can establish the following bloc scheme of the wind system.

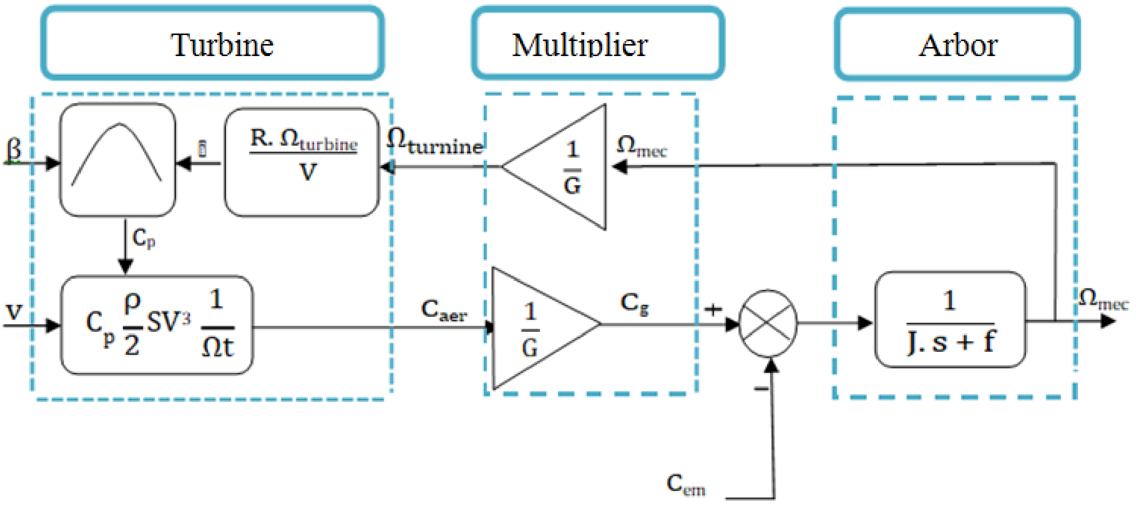

Figure II- 2 : Bloc Scheme of the wind system **[14]**.

2.2.3 BETZ limit

The power coefficient Cp represents the aerodynamic efficiency of the wind turbine and also depends on the characteristic of the turbine. This coefficient has a theoretical limit, known as the Betz limit, equal to 0.593 and which is never reached in practice [Heier, 1998].

Within the framework of this thesis, we will use an approximate expression of the coefficient of power as a function of the relative speed λ and the angle of inclination of the blades β, of which the expression originates from the work of El Aimani [El Aimani, 2003]:

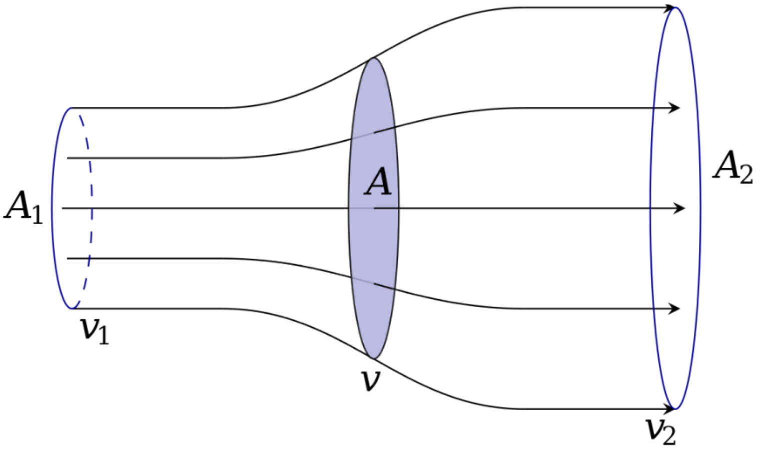

Figure II- 3 : Tub of air current around a wind turbine.

In short, what BETZ has proven in a nutshell is that in the best conditions we can only harness 59% of the wind energy that hits the propellers.

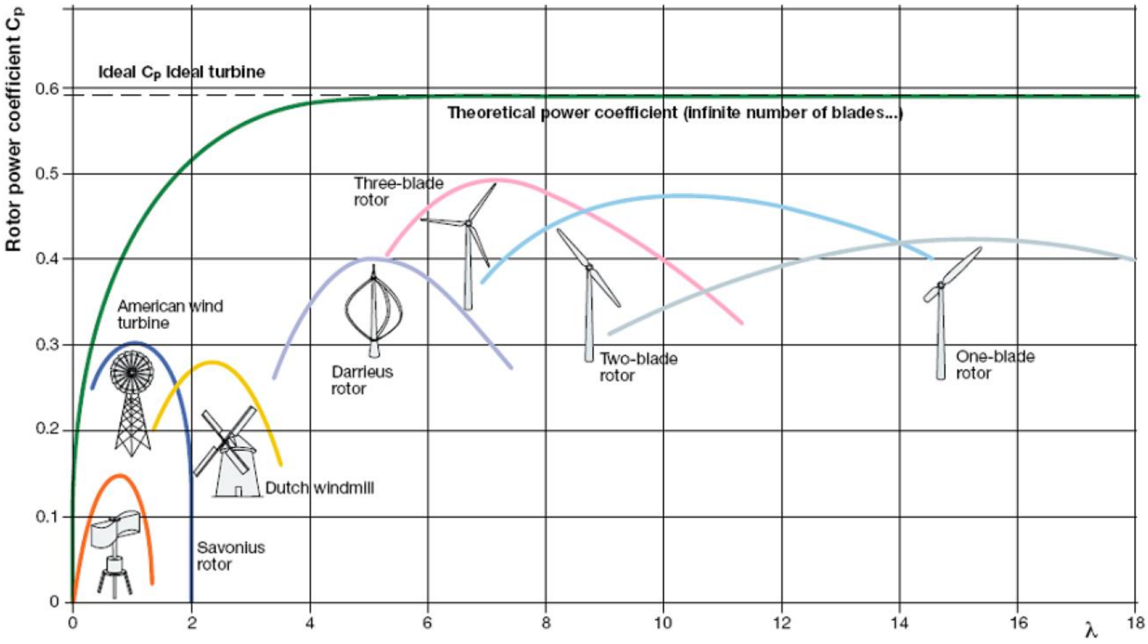

Figure II- 4 : Power coefficient for different types of wind turbines **[15].**

2.2.4 Power coefficient Cp

Several numerical approximations have been developed in the literature to determine an expression for the coefficient Cp **[16]:**

1. First expression

$$Cp = \frac{1}{2}(\gamma - 0{,}022\beta^2 - 5{,}6)e^{-0.17\gamma} \tag*{(II. 9)}$$

$$\gamma = \frac{9\,V_w}{4\,\Omega} \tag*{(II. 10}$$

γ : is the peripheral speed ratio;

β : represents the angle of attack of the blade in degrees.

2. Second expression

$$Cp = 0{,}73\left(\frac{151}{\lambda'} - 0{,}58.\beta - 0{,}002.\beta^{2{,}14} - 13{,}2\right)e^{\frac{-18.5}{\lambda}} \tag*{(II. 11)}$$

With:

$$\frac{1}{\lambda'} = \frac{1}{\lambda + 0.02\beta} - \frac{0.003}{\beta^3 + 1} \tag*{(II. 12)}$$

3. Third expression

$$Cp = (0{,}44 - 0{,}0167\beta).sin\left[\frac{\pi(\lambda - 3)}{15 - 0{,}3.\beta}\right] - 0{,}00184.(\lambda - 3)\beta \tag*{(II. 13)}$$

4. Fourth expression

$$Cp = 0{,}5176\left(\frac{116}{\lambda'} - 0{,}4.\beta - 5\right)e^{\frac{-21}{\lambda'}} + 0{,}0068.\lambda \tag*{(II. 14)}$$

With:

$$\frac{1}{\lambda'} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \tag*{(II. 15)}$$

This last expression is part of the SIMULINK library, and therefore will be the one used to validate the model of our wind system. The curve of this last formula is given by Figure(I.5) Several curves are represented on this figure depending on the angle of attack β, but in this thesis we will only be interested in the one corresponding to β=0. This is because on a small wind turbine there is no way to change the pitch angle of the blades as this means producing a more expensive wind turbine.

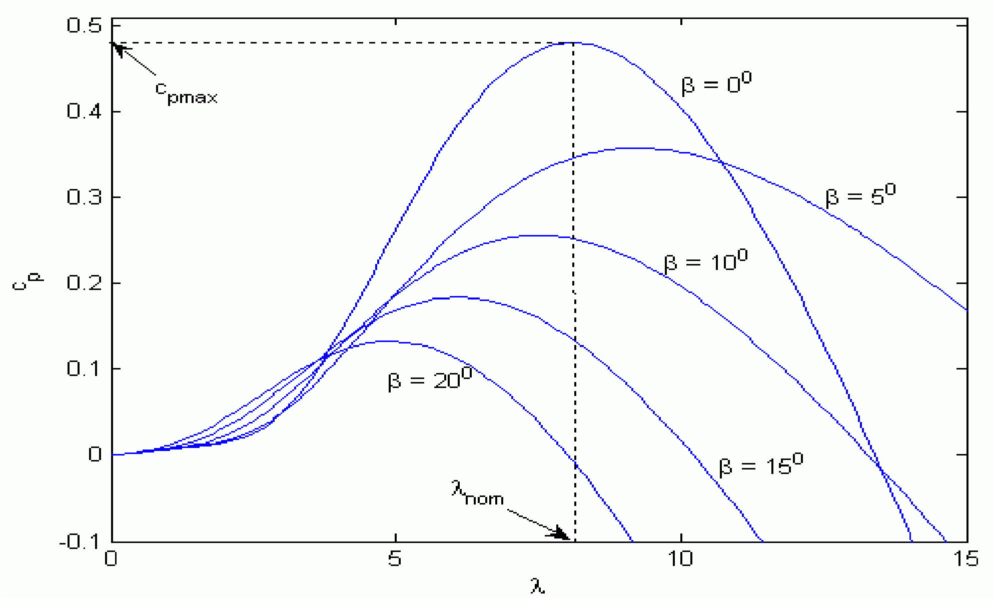

Figure II- 5 : CP curve from SIMULINK model **[17].**

2.3 DC generator modelling

The generator used in our work to convert the turbine mechanical power in electric power is a DC generator which will be described in this paragraph. Generally, a machine is an electromechanical converter allowing the bidirectional conversion of energy between an electrical installation through which a direct current flows and a mechanical device. It is also called dynamo.

2.3.1 Construction

Before arriving to the mathematical model of the DC machine which will be used for the machine simulation, we must describe the machine and we begin by its construction. In fact, the main elements of the DC machine are shown in Figure (II.9):

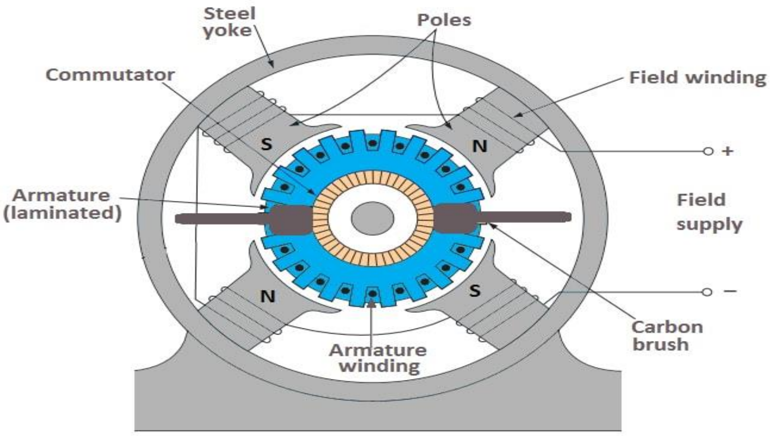

Figure II- 6 : DC motor.

a) Inductor

It is the fixed part of the motor, whose main function is to create the necessary magnetic excitation field for machine operating. It is constituted either by a permanent magnet or by an electromagnet whose windings are traversed by the direct current of excitation.

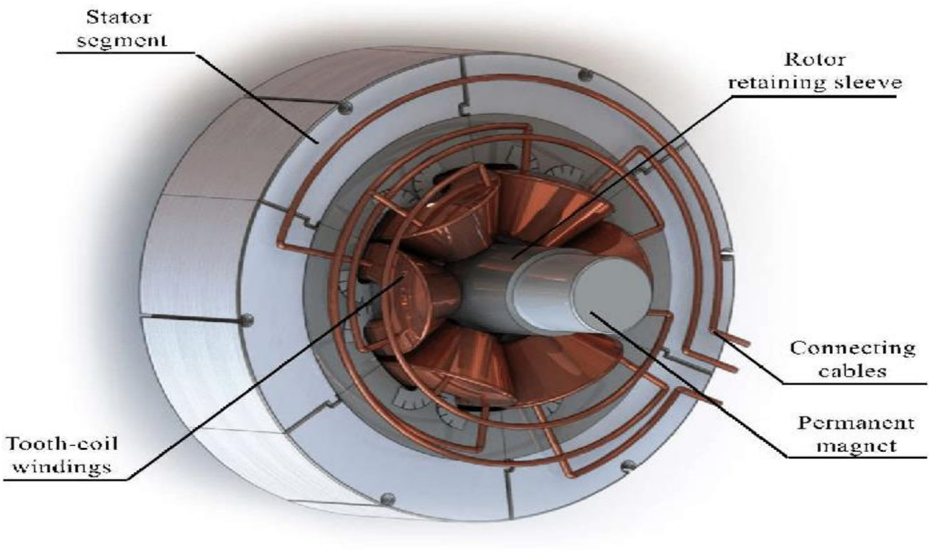

Figure II- 7 : Inductor (Stator) of the DC machine.

When the inductor is not constitute with permanent magnets, it consists of coil fed by a direct current (Ie), called excitation current. It is then equivalent to its resistance in series with the coil.

b) Rotor

This is the moving part of the machine, which includes one or more coils rotating in the magnetic field (Figure II- 8).

Figure II- 8 : Armature.

2.3.2 DC machine symbole

There are two symbols to for DC machine which are presented in Figure (II-9)

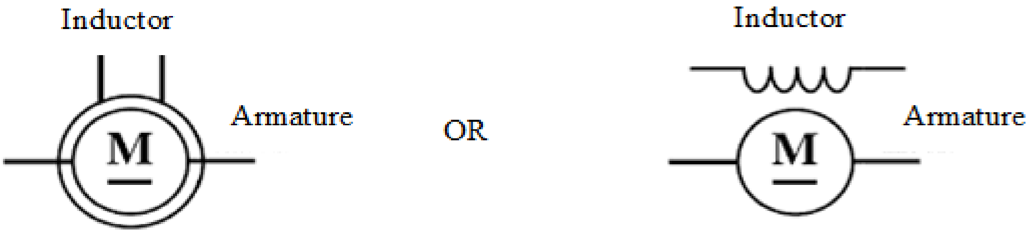

Figure II- 9 : DC machine symbol **[12].**

2.3.3 Principle of operation

The inductor (or Stator) creates a magnetic field $\vec{B}$. This stator can be made up of permanent magnets or electromagnets.

The armature (or Rotor) carries conductors, in the form of turns traversed by a direct current; these whorls subjected to the forces of Laplace involve the rotation. Indeed, the variation of the field flux through the turns, generates an electromagnetic force (emf) induced in the rotor, which is rectified by the assembly (collectorballais). The value of this e.m.f.is proportional to the mechanical speed of the Dc machine(Ω_m) and the magnetic flux (φ) and it is expressed as follows:

$$E = K\Omega_m\varphi \tag{II. 16}$$

Where,

Ω_m: Mechanical machine speed (rd/s);

φ: The magnetic flux provided by the stator.

2.3.4 Equivalent diagram of a DC machine

The motor behaves like a resistor in series with a voltage generator(EMF: electromotive force).

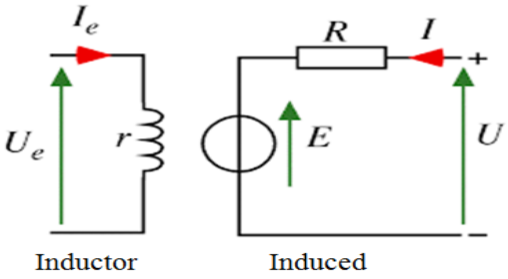

Figure II- 10 : Equivalent diagram of a DC machine.

2.3.5 Different DC machine Excitation Modes

There are four excitation modes for the DC machine which are described hereafter:

a) Series excitation:

In this case of excitation, the magnetic field circuit is placed with the motor rotor. Its particularity is to have an inductor which is crossed by the same current as the inductor. Therefore has a lower resistance than that of other types of machines. The inductor is in series with the armature (rotor). The main advantage of this excitation type is the single power source. The direction of rotation is changed by swapping the connections of the armature and the inductor. The machine electric circuit is represented by the following figure.

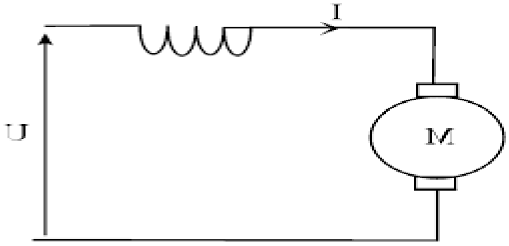

Figure II- 11 : Electrical modeling of a series excitation motor.

b) Shunt excitation

In this excitation type, the winding is connected in parallel to the motor supply it has the same properties as the separately excited motor because, in both cases, the inductor constitutes a circuit external to that of the armature. The electrical circuit is represented by the following figure. Also in this case one power source is necessary.

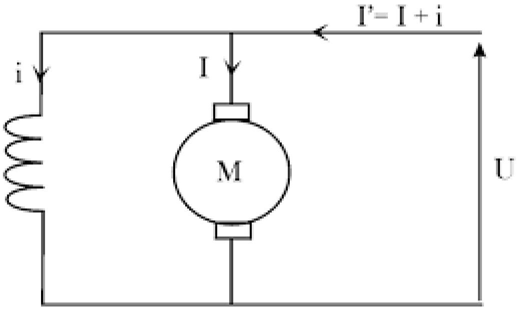

Figure II- 12 : Electrical modeling of a shunt excitation motor.

c) Compound excitation

The compound excitation motor is composed from two excitations (serie excitation and shunt excitation) at the same time. The following figure shows the machine electrical circuit.

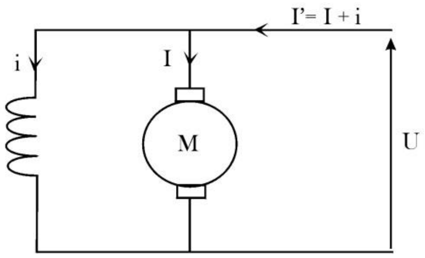

Figure II- 13 : Electrical modeling of a compound excitation motor.

d) Separately excited motor

This mode of excitation requires two separate power sources. The power supply for the field winding is taken from a source independent of the main source of the rotor. The direction of rotation is changed by swapping the terminals of the armature or the inductor. The machine electrical circuit is shown in the following figure:

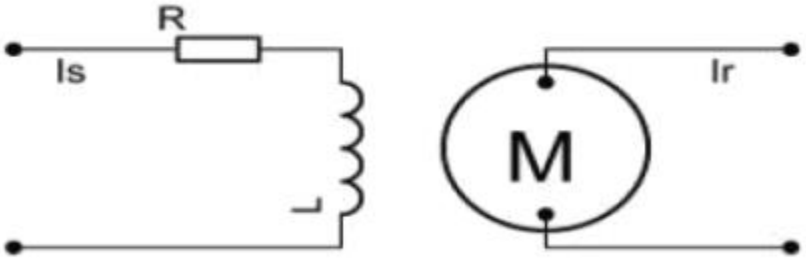

Figure II- 14 : Electrical modeling of a DC machine with separate excitation.

2.3.6 DC machine modelling

To its simplicity, the separated excitation mode is chosen for the DC machine used in this work. The equivalent electrical model of the DC machine of our DC machine is presented in Figure.

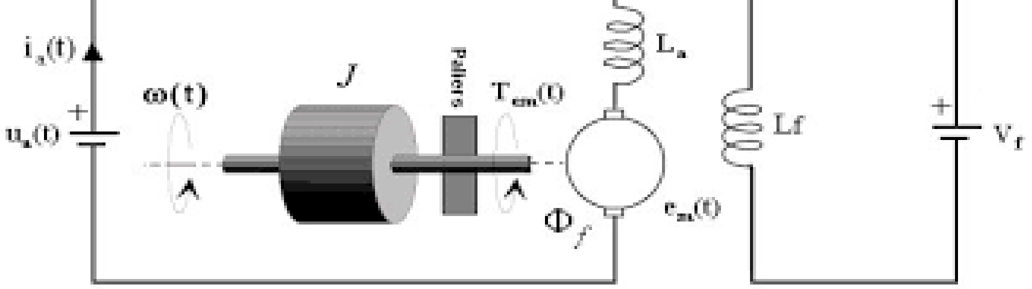

Figure II- 15: Electrical model of the separated excitation DC-machine **[18]**.

The mathematical model of the permanent magnet DC machine is formed by three equations (electrical question, mechanical equation and electromagnetic torque equation) as expressed hereafter:

a. Electrical equation

$$U_a(t) = R_a i_a(t) + L_a \frac{di_a(t)}{dt} + E_a \qquad \text{(II. 17)}$$

b. Mechanical equation

$$Cem = J \frac{d\Omega}{dt} + f\Omega + cr \qquad \text{(II. 18)}$$

c. Electromagnetic torque

$$cem = k\varphi Ia = Km\Omega \qquad \text{(II. 19)}$$

d. Electromagnetic force

$$Ea = K\varphi\Omega \qquad \text{(II. 20)}$$

Where,

R_a and L_a are respectively the machine resistor

(Ω) and machine inductance (H);

J and f are respectively the machine inertia (kg/m^2);

Friction (N.s/m);

$Km$is torque constant;

Cr is the load torque (N.m).

2.3.7 DC machine Four-Quadrant Operation

The four quadrants of the operation of a DC machine is presented in the following figure

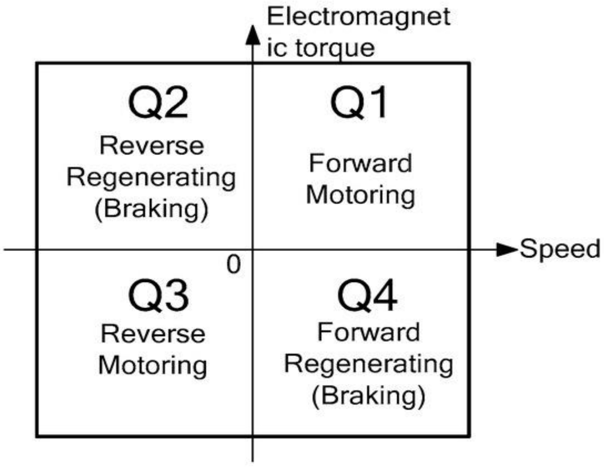

Figure II- 16: DC machine Four-Quadrant Operation.

Quadrant 1: The machine spins forward and runs as a forward motor;

Quadrant 2: The machine rotates forward and operates as a generator;

Quadrant 3. The machine rotates backwards and operates as a reverse motor;

Quadrant 4. The machine rotates backwards and operates as generator.

2.4 H bridge modelling

In order to permit to DC machine to operate in the four quadrant described previously, an H bridge chopper is necessary whose model is given hereafter:

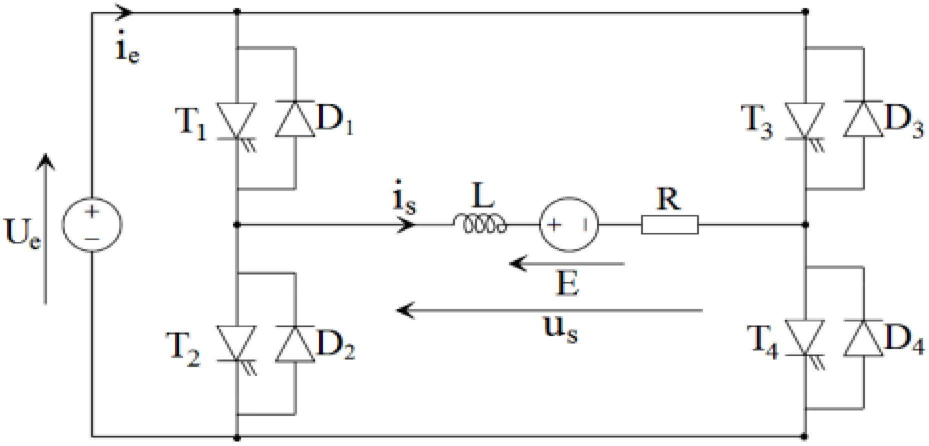

Figure II- 17 : Structure of the four-quadrant chopper controlling the DC machine.

The DC machine is likely to operate as a motor where the energy transfer takes place from the source U_e to the DC machine or as a generator where the energy transfer takes place from the DC machine to electrical source U_e.

The switches consist of an IGBT or MOSFET transistor is composed from transistor in parallel with diode in order to ensure motor and the generator operation. In fact, in the case of motor operation, the current conduction is established by the transistor, and in the generator mode situation, the current conduction is ensured by the diode. This assembly allows operation in the 4 quadrants as follow:

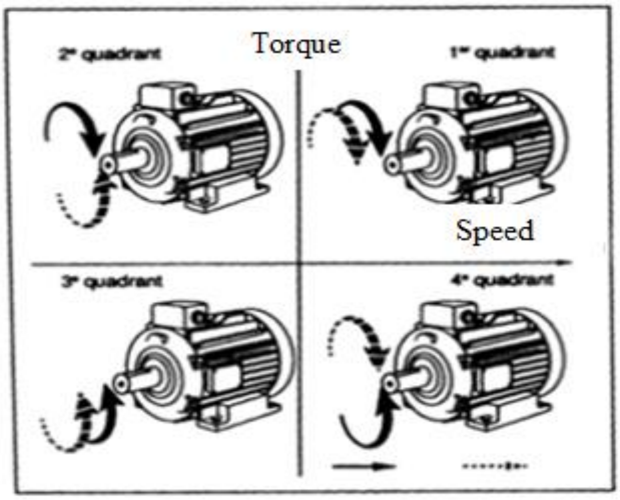

Figure II- 18 : Front motor and generator operation.

The H bridge model is as following:

The instantaneous voltage of the DC machine is expressed in function of source voltage and switching command (H) as follow:

$$Us = (2H - 1)Ue \qquad \text{(II. 21)}$$

In the same way, the source current is expressed as a function of DC machine current and the H command as follows:

$$ie = (2H - 1)is \qquad \text{(II. 22)}$$

The mean value of the DC machine voltage can be easily obtained by writing the mean value of the equation (II.2).

$$< Us >= (2\alpha - 1)Ue \qquad \text{(II. 23)}$$

Where,
$\alpha$is duty cycle ($0 < \alpha < 1$).

After DC machine and H bridge modelling, the final model of the DC machine associated to the H bridge chopper is given by following state variable model **[12]:**

$$\begin{cases} (2H - 1)E = Raia + (L + La)\frac{dia}{dt} + KM\Omega & \text{(II. 24)} \\ KMia = J\frac{d\Omega}{dt} + f\Omega + Cr & \text{(II. 25)} \end{cases}$$

This can easily be written in the following state form:

$$\begin{cases} dia/dt = \frac{(2H-1)E}{L+La} - \frac{Ra}{L+La}ia - \frac{KM}{L+La}\Omega & \text{(II. 26)} \\ \frac{d\Omega}{dt} = \frac{KM}{J}ia - \frac{f}{J}\Omega - \frac{Cr}{J} & \text{(II. 27)} \end{cases}$$

2.5 Inverter modelling

Generally, the inverter is a static converter which allows the adjustment of the power transfer between a direct current or voltage source and an alternating current or voltage source. It connects a structure of DC voltage or current to a single-phase or three-phase receiver of AC current or voltage.

The frequency "*f*" of the alternative source is:

a. Either imposed (fixed or adjustable), by an autonomous electronic control (autonomous power system).

b. Either imposed constant by the source itself (assisted inverter debited on the network).

c. Either imposed, variable by the source itself (inverter supplying a machine synchronous, controlled by the frequency of the emf. of the machine). The standardized inverter symbol is shown in the following figure:

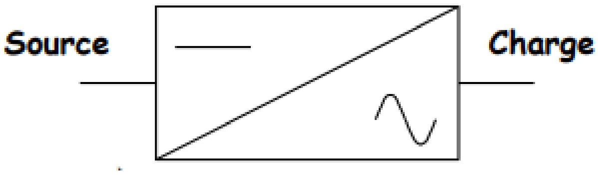

Figure II- 19: Standardized inverter symbol **[19].**

Figure shows the structure of a three-phase inverter that connects a DC voltage source to a three-phase current receiver.

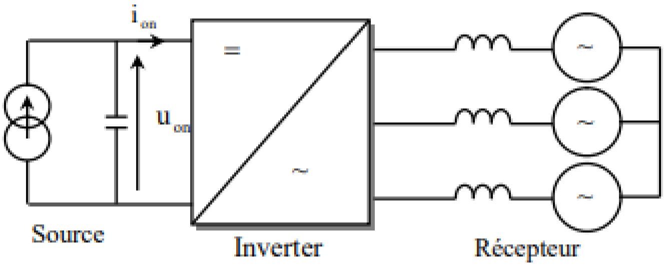

Figure II- 20 : Structure of a three-phase voltage inverter **[20].**

2.5.1 Types of voltage inverters

There are two types of inverters which are used in practice which are described hereafter:

a) Single phase voltage inverter

The single voltage inverter circuit for obtaining an alternating voltage from a direct voltage using four switches is presented in the following figure:

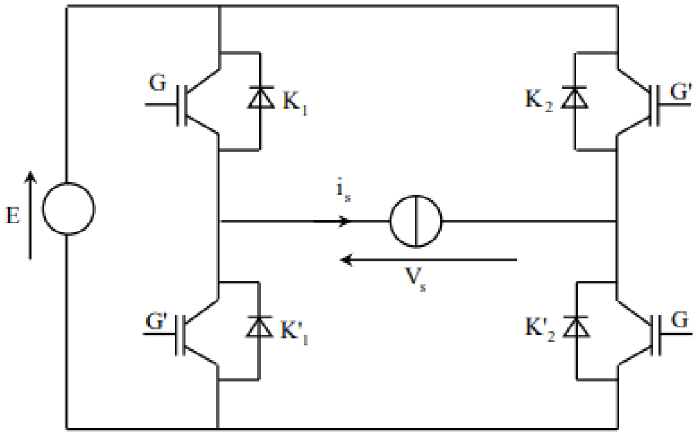

Figure II- 21 : Bridge Voltage Single Phase Inverter using one DC source **[20].**

The instantanous model of this inverter is given by:

$$Vs = (2G - 1)E \qquad \text{(II. 28)}$$

Where, G is the command signal obtained by a PWM technique (this technique will be developed later in this work)which is necessary to obtain an alternating voltage with a desired frequency from the DC source.

c)Three-phase inverters

The three-phase voltage inverter circuit is shown by figure. As shown, it formed by three single-phase half bridges. Each half bridge comprises a thyristor (or a transistor) and a diode **[20]**.

The DC voltage source (V_{pv}) can be obtained from a bridge rectifier or a battery voltage or a regulate DC link voltage as will be shown later in the future chapter. To ensure the continuity of the AC output currents Ia, Ib, Ic, the switches S1, S'1 and S2, S'2, S3 and S'3 must be complementary in pairs. We define Si = (Ti, Di)

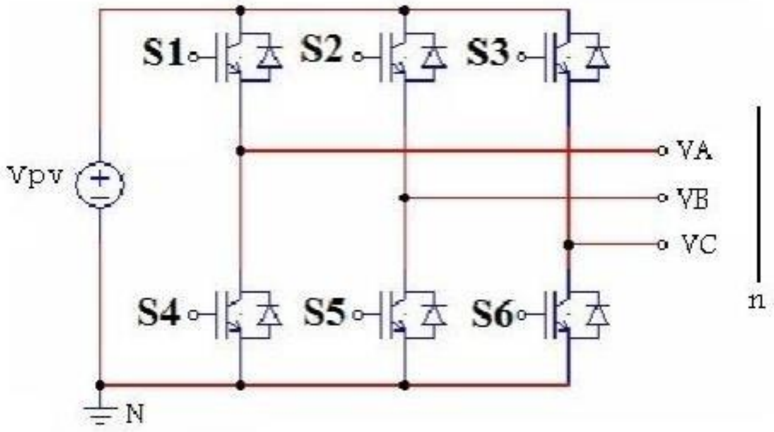

Figure II-22 : Three-phase Full –Bridge Inverter.

2.5.2 Grid-Side converter modeling

As has been mentioned, the inverter assembly consists of six bidirectional switches, each switch consists of a transistor (T) and a diode (D) mounted head to tail The pairs of switches (S1, S'1), (S2, S'2) , (S3, S'3) are controlled in a complementary way, to ensure the continuity of the currents in the load on the one hand, and to avoid the short-circuit of the source on the other hand. To guard against an untimely short-circuit, it is necessary to leave a small time interval between the closing command of Si and Si' (i=1,2,3) . The diodes Dij ($i\in$ [1,2], $j\in$ [1, 2,3]) are free-wheeling diodes providing the current conduction from the load to the DC source.

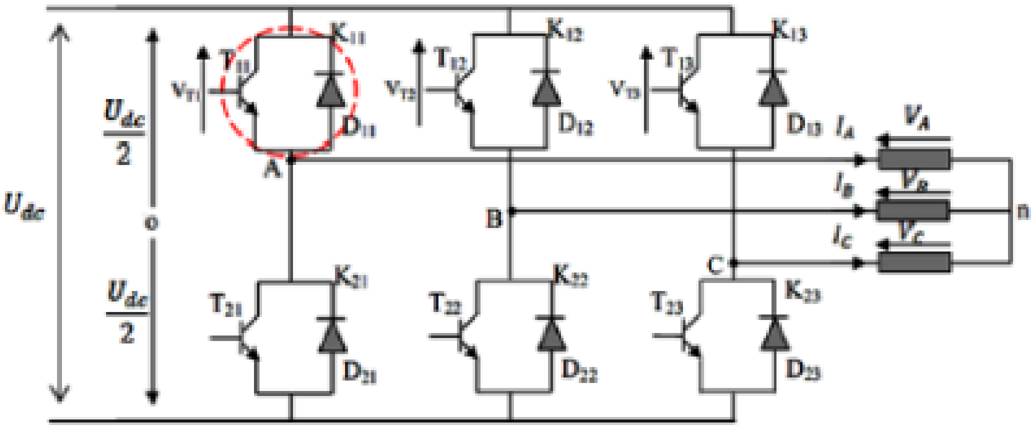

Figure II-13: Three Phase Two Level Voltage Inverter.

From the circuit (Figure II-23), one can write:

$$\begin{cases} V_{Ao} = V_{An} + V_{no} \\ V_{Bo} = V_{Bn} + V_{no} \\ V_{Co} = V_{Cn} + V_{no} \end{cases} \tag{II. 29}$$

As the load is a three-phase load (alternating machine for example) the system V_{An}, V_{Bn} and V_{CN}being balanced (V_{An} + V_{Bn} + V_{Cn} = 0), we will therefore write:

$$V_{no} = \frac{V_{Ao}+V_{Bo}+V_{Co}}{3} \tag{II. 30}$$

Replacing this last equation in equation, we obtain:

$$\left\{\begin{matrix} V_{An} = \frac{2V_{Ao}-V_{Bo}-V_{Co}}{3} \\ V_{Bn} = \frac{-V_{Ao}+2V_{Bo}-V_{Co}}{3} \\ V_{Cn} = \frac{-V_{Ao}-V_{Bo}+2V_{Co}}{3} \end{matrix}\right\} \tag{II. 31}$$

On the other hand, from the electrical circuit (Figure II-23), one can write:

$$V_{Ao} = \begin{cases} \frac{U_{dc}}{2} \ \ if\ S1 = 1 \\ -\frac{U_{dc}}{2} \ \ if\ S1 = 0 \end{cases} \tag{II. 32}$$

$$V_{Bo} = \begin{cases} \frac{U_{dc}}{2} \ \ if\ S2 = 1 \\ -\frac{U_{dc}}{2} \ \ if\ S2 = 0 \end{cases} \tag{II. 33}$$

$$V_{Co} = \begin{cases} \frac{U_{dc}}{2} \ \ if\ S3 = 1 \\ -\frac{U_{dc}}{2} \ \ if\ S3 = 0 \end{cases} \tag{II. 34}$$

So, one can write:

$$\left\{\begin{matrix} V_{Ao} = (2S_1 - 1)\frac{U_{dc}}{2} \\ V_{Bo} = (2S_2 - 1)\frac{U_{dc}}{2} \\ V_{Co} = (2S_3 - 1)\frac{U_{dc}}{2} \end{matrix}\right\} \tag{II. 35}$$

By replacing equation (II.37) in equation (II.33), we obtain the mathematical model of the two level three phase inverter as follows:

$$\begin{bmatrix} V_{An} \\ V_{Bn} \\ V_{Cn} \end{bmatrix} = \frac{U_{dc}}{3}\begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix}\begin{bmatrix} S_1 \\ S_2 \\ S_3 \end{bmatrix} \tag{II. 36}$$

In addition, the relationship between the current modulated by the innverter (Idc) and the three-phase alternating currents (ia, ib and ic) is defined by the following equation:

$$\boldsymbol{I}_{dc} = [\boldsymbol{S}_1 \quad \boldsymbol{S}_2 \quad \boldsymbol{S}_3]\begin{bmatrix}\boldsymbol{I}_A\\ \boldsymbol{I}_B\\ \boldsymbol{I}_C\end{bmatrix} \tag{II. 37}$$

2.5.3 Grid connecting line modeling

Note that the determination of the logical states (Fi) and (Si) of the interceptors depends on the control strategy to be applied to the MSC and GSC. By applying the lattice law, we can write the mathematical relations linking the voltages of the output of the GSC to the network voltages as follows:

$$\begin{aligned} V_{ag} &= R_g i_{ag} + L_g \frac{di_{ag}}{dt} + V_{ainv}\\ V_{bg} &= R_g i_{bg} + L_g \frac{di_{bg}}{dt} + V_{binv}\\ V_{cg} &= R_g i_{cg} + L_g \frac{di_{cg}}{dt} + V_{cinv} \end{aligned} \tag{II. 38}$$

The application of the Park transformation to the last equations, allows us to obtain:

$$\begin{cases} V_{dg} = R_g i_{dg} + L_g \frac{di_{dg}}{dt} + \varphi_s L_g i_{qg} + V_{dinv}\\ V_{qg} = R_g i_{qg} + L_g \frac{di_{qg}}{dt} - \varphi_s L_g i_{dg} + V_{qinv} \end{cases} \tag{II. 39}$$

2.6 Modelling of the continuos bus

The following figure represents the DC bus and we can see that it is represented by the capacitor where the two converters are connected.

The coupling of the two static converters (rotor side and network side) is done via a DC bus, it is therefore necessary to have the mathematical model of this circuit

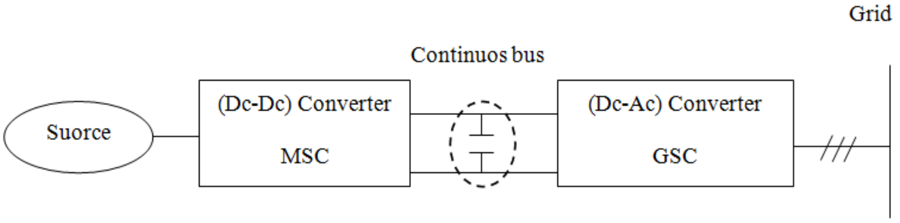

Figure II- 24 : DC-bus scheme.

The time evolution of the DC bus voltage is obtained from the integration of the capacitive current

$$\frac{dU_C}{dt} = \frac{1}{c} i_C \tag{II. 40}$$

$$U_C(t) = U_C + \frac{1}{c}\int_{t_1}^{t_2} i_c dt \tag{II. 41}$$

The adjustment of the DC bus is carried out by means of a regulation loop making it possible to maintain a constant voltage of the DC bus, with an integral proportional corrector generating the reference of the current to be injected into the capacitor (ic-ref).**[21]:**

2.7 Conclusion

This chapter is devoted to the studied wind system modelling. Firstly, the general electric circuit of the proposed system is presented. Next, all the system components are described and there mathematic models are established. In fact, at the beginning, we have described all equations for turbine operation. In the second we have considered the DC machine associated to the H bridge chopper modeling. All required equations of them are established. Inverter, three-phase line between the grid and inverter finished the wind system modelling. Now, all system components are ready to be considered for control strategies application to ensure some performances in the closed loop in the next chapter.

Chapter 3: Control of the Wind Energy system

3.1 Introduction

In the previous chapter we have interested on the wind system modelling. In this chapter we will focus on developing control strategies that will be applied to the system in order to achieve some performances in the closed loop.

In fact, a PI controller is developed and applied to the DC generator in order to ensure the MPPT mode and extract the maximum power from the wind. Also, another PI controller is applied to the inverter in such a way to inject the produced power in the grid by controlling the DC bus voltage. Finally, a last PI controller is applied to a mechanical load based on DC machine in order to regulate its speed to a desired value with a torque load. All the obtained simulation results are presented and discussed.

3.2 PWM control strategies

Several control types (hysteresis current control, sinusoidal triangle control, etc...) can be applied to the bridge chopper and to the inverter to ensure the desired performances. In our case and for its simplicity, we have limited ourselves to the application of the current hysteresis PWM strategy which is described hereafter:

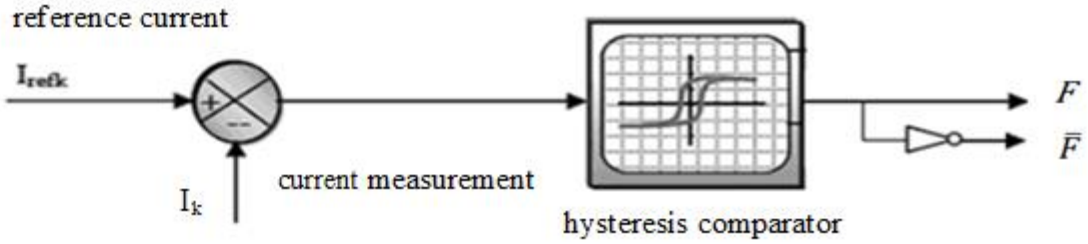

Figure III- 1 : Inverter arm hysteresis controller.

The switching on and blocking pulses of the inverter switches are generated using a hysteresis comparator to limit the phase current in the hysteresis band (ΔI)Consequently, the three static switches' switching conditions are (I= a ,b ,c),the inverters are defined in terms of the corresponding Logic states as follows:

$$\mathrm{Fi} = 1 \text{ si } I_{\mathrm{ref}} - I_{\mathrm{k}} > \Delta I \quad \text{(III-1)}$$

$$\mathrm{Fi} = -1 \text{ si } I_{\mathrm{ref}} - I_{\mathrm{k}} < \Delta I$$

The principle of this technique is detailed in the following figure:

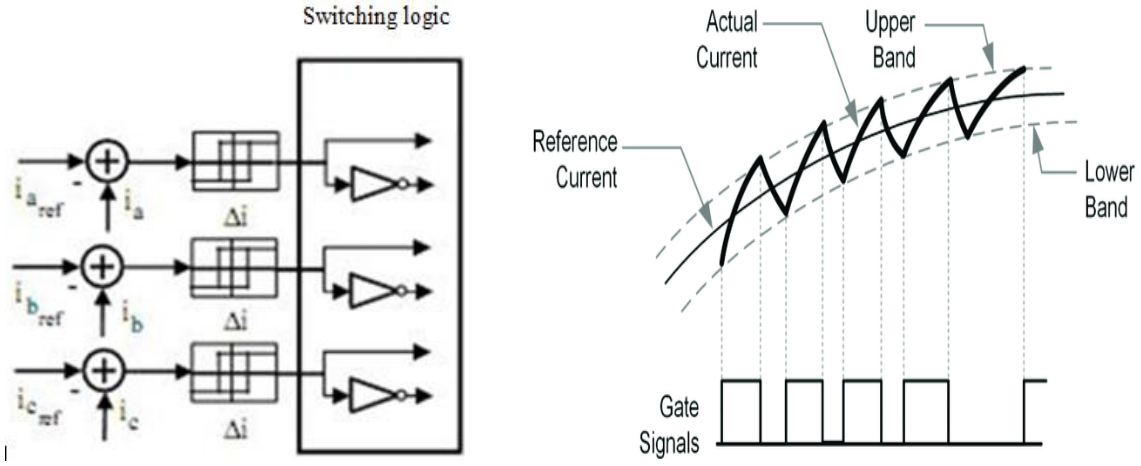

Figure III-2: Control by current hysteresis for three phases

$$\begin{cases} F_1 i = 1 \; si \; I_{iaref} - I_a > \Delta I \\ F_1 i = -1 \; si \; I_{iaref} - I_a < \Delta I \end{cases} \qquad \text{(III-2)}$$

$$\begin{cases} F_2 i = 1 \; si \; I_{ibref} - I_b > \Delta I \\ F_2 i = -1 \; si \; I_{ibref} - I_b < \Delta I \end{cases} \qquad \text{(III-3)}$$

$$\begin{cases} F_3 i = 1 \; i \; I_{icref} - I_c > \Delta I \\ F_3 i = -1 \; si \; I_{icref} - I_c < \Delta I \end{cases} \qquad \text{(III-4)}$$

3.3 Control strategies applied to MSC (H-Bridge)

The main objective of controlling the MSC (Bridge Chopper) is to extract the maximum power from the wind. So, in order to ensure the MPPT mode, the power coefficient (Figure III-3) must be kept at the maximum value by controlling the generator speed.

To see the result of our simulation we use a Matlab script program

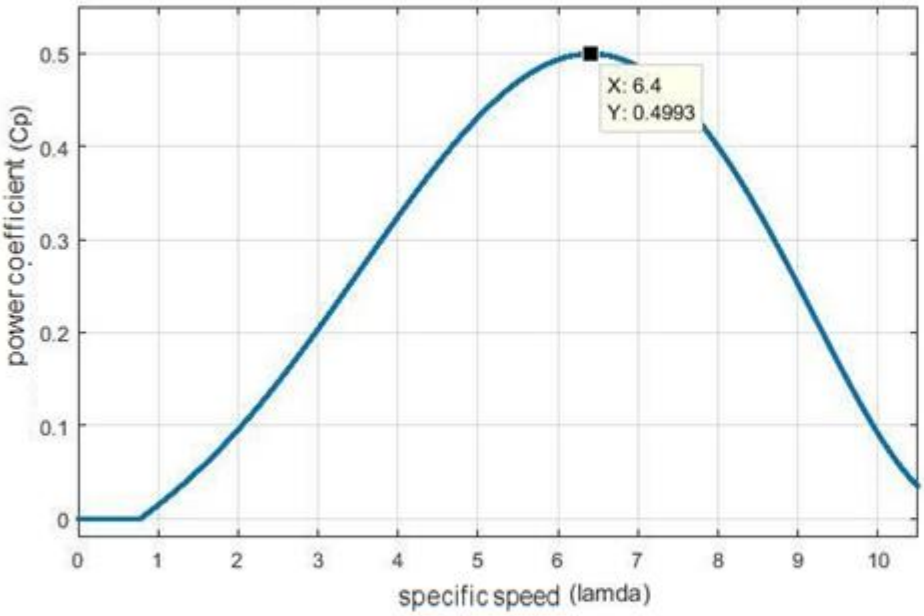

Figure III- 3 : Power coefficient as a function of the specific speed λ

To extract the maximum power from the wind and achieve the so-called MPPT (Maximum Power Point Tracking), it is necessary to ensure that the set speed (λ) remains practically equal to its optimum value, for each wind speed (v), expressed by:

$$\lambda_{op} = \frac{\Omega_{tref}.R}{v} \qquad \text{(III-5)}$$

Therefore the speed of the DC-generator must follow its reference value given by:

$$\Omega_{gref} = \frac{\lambda_{op}.v}{R}.G \qquad \text{(III-6)}$$

3.4 PI Speed controller

In order to ensure that the speed generator follows the reference (equation III.6) and achieve the MPPT, a PI controller is considered whose parameters are calculated basing on the mechanical equation of the generator (Figure III-4) as follows:

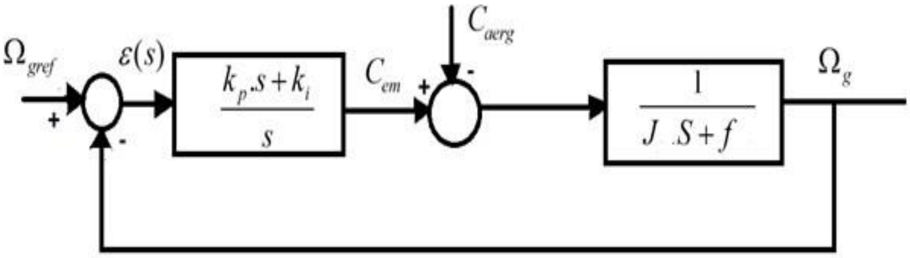

Figure III- 4 :PI controller of the generator speed .

The standard transfer function of a PI regulator is as follows:

$$\frac{Uref(S)}{\varepsilon(S)} = \frac{(KpS+Ki)}{S} \qquad \text{(III-7)}$$

The open loop system transfer function is:

$$G_0(S) = \left(\frac{K_p .S+Ki}{S}\right)\left(\frac{1}{J.S+f}\right) \qquad \text{(III-8)}$$

And therefore the closed loop transfer function is easily obtained:

$$G_F(S) = \frac{(K_pS+Ki)}{JS^2+(f+K_p)S+K_i} \qquad \text{(III-9)}$$

We notice that the dynamics of the closed-loop transfer function is of second order. Its characteristic polynomial is of the following form

$$P_1(S) = \frac{R_s}{w_0^2}S^2 + \frac{2\varepsilon}{w_0^2}S + 1 \qquad \text{(III-10)}$$

ε : The damping coefficient;

w_0: System pulse.

By comparing the equation (III-10) and the denominator of the equation (III-9), we easily find the two gains of the PI regulator as follows:

$$K_i = Jw_0^2 \ and \ \frac{2\varepsilon Ki}{w_0} - f \qquad \text{(III-11)}$$

Note that the parameters (J and f) are obtained by machine identification.

Finally, the detailed control scheme of the GSC control based on PI controller to ensure MPPT is given by the following figure:

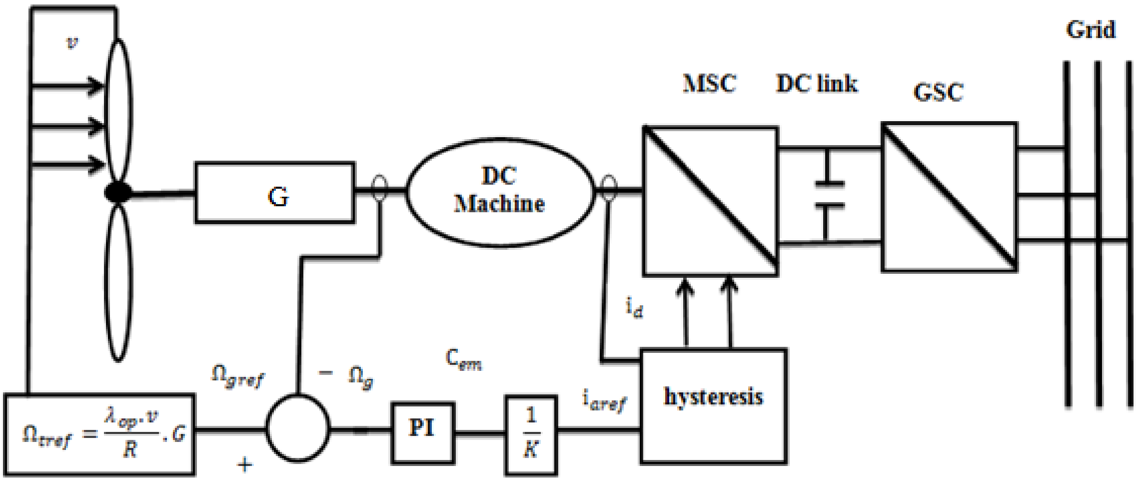

Figure III- 5: Control scheme of the MSC.

In order to show that the wind system is operated in the MPPT mode, a wind speed waveform is applied.

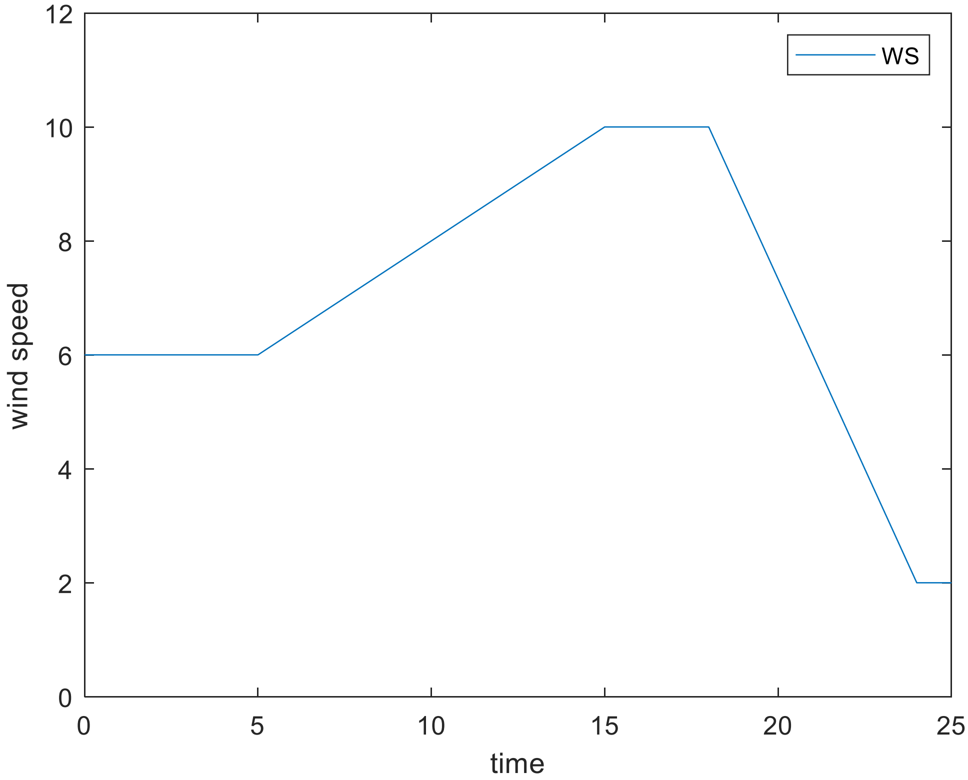

Figure III- 6 : Wind speed curve (*m/s*).

The following figures illustrate the obtained simulation results.

According to Figure (Figure III-7) the generator speed (Ω_g) follows the optimal reference speed (Ω_{gref}) to extract the maximum power and ensure the system operation in the MPPT mode. Moreover, the power coefficient C_p remained close to its optimal value (C_{popt}=0.4993) (see figure III-8). Also, the specific speed is kept at its optimum value (λ_{opt}=6.4) (see figure III- 9) during the wind speed variation.

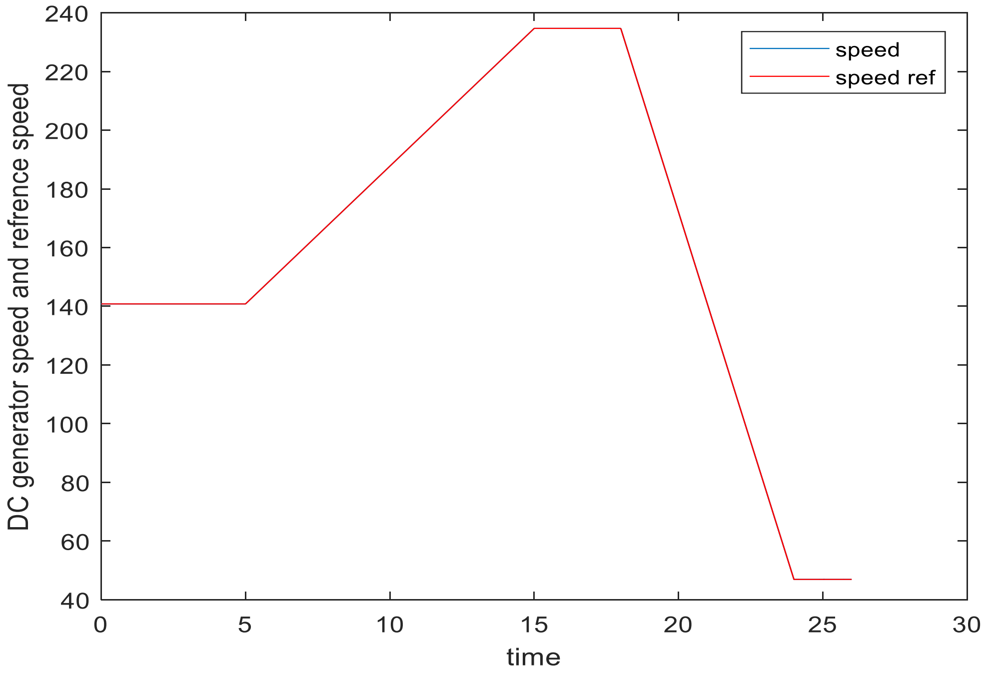

Figure III- 7 : Generator rotational speed with its reference (rad/s).

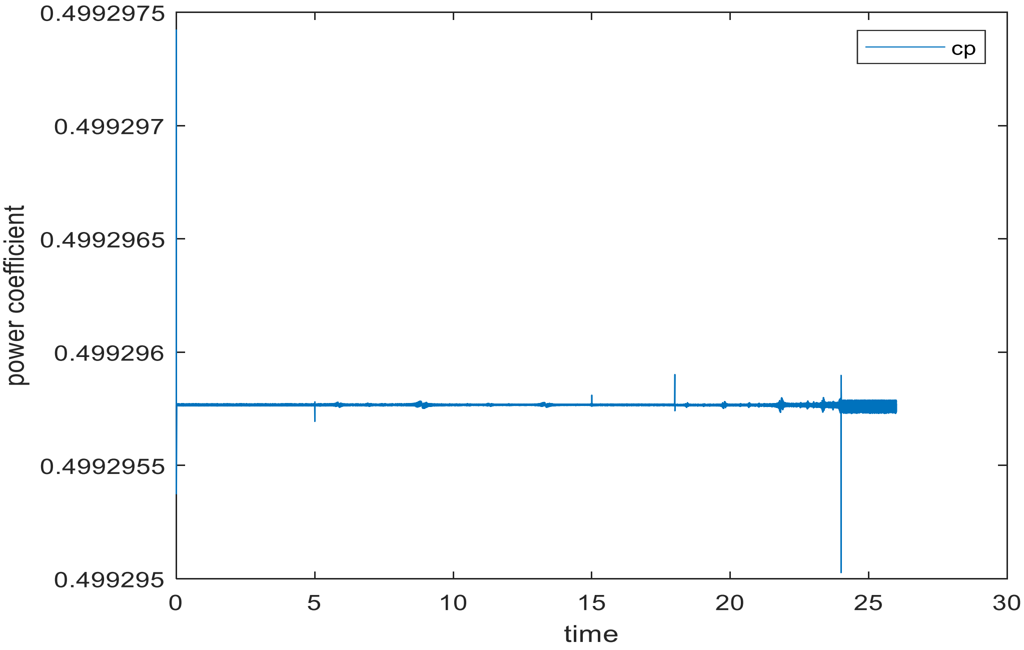

Figure III- 8 : Curve of the power coefficient (Cp).

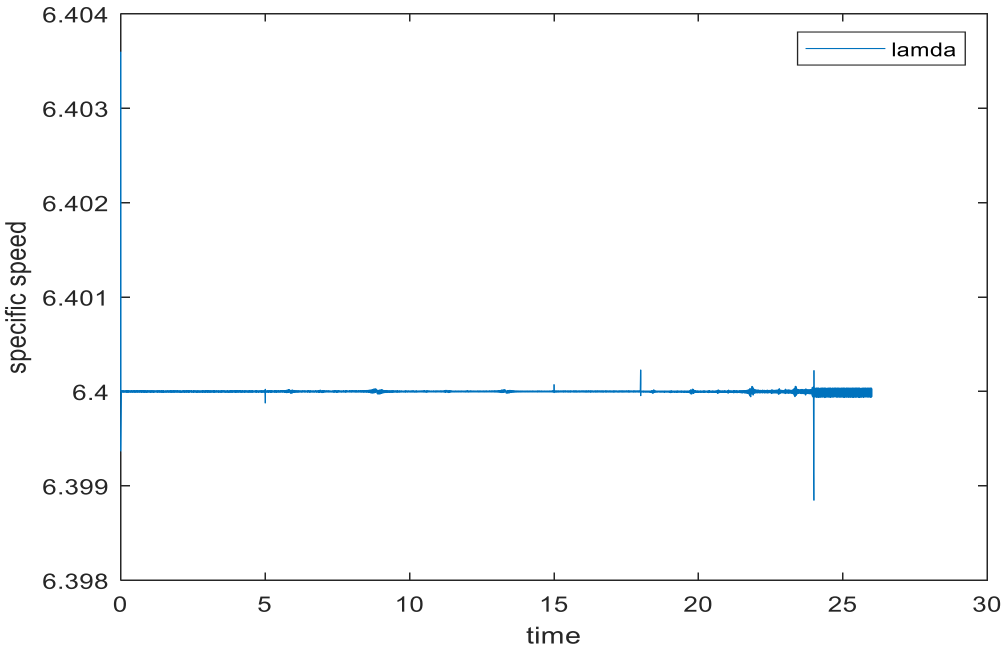

Figure III- 9 :Curve of the specific velocity (λ).

Figure (III-10) presents the current (i_a) of the DC-generator with its reference (i_{aref}). By comparison of figures (III-6) and (III-10), we notice that the generator current increases and decreases with the wind speed variation and it has a negative value which means that the generator produces active power and supplies it to the DC link bus .In other words, the DC-generator produces through its armature the maximum power extracted from the wind.

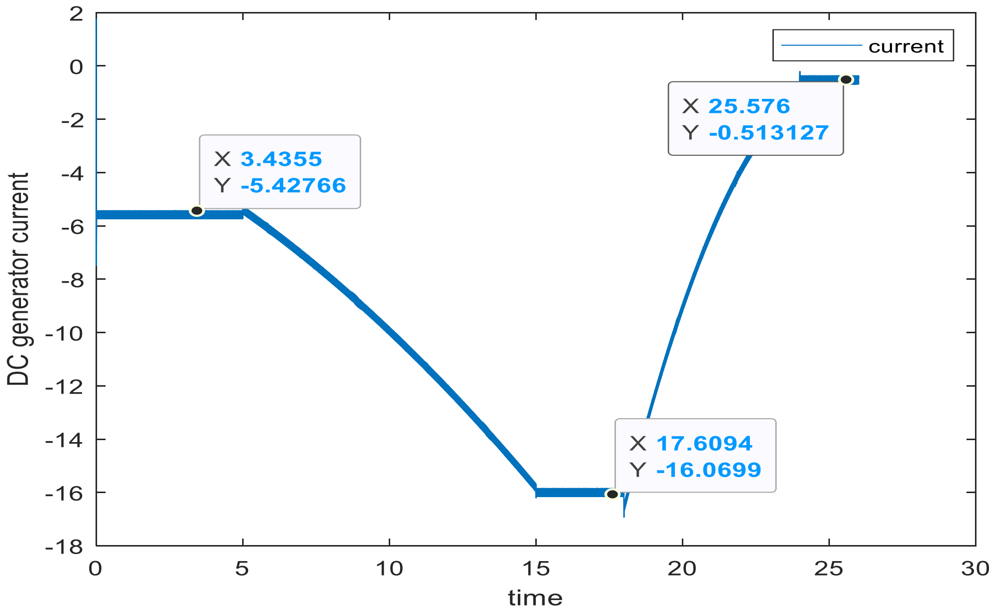

Figure III-10 : DC-generator current (i_a) with its reference i_{aref} (A).

Figure (III-11) shows the captured wind power (P_w) with its maximum produced wind power (P_{wmax}). From this figure, one can see that the wind power follows its references maximum power which means that the maximum power is captured and is available to be either used or injected in the grid.

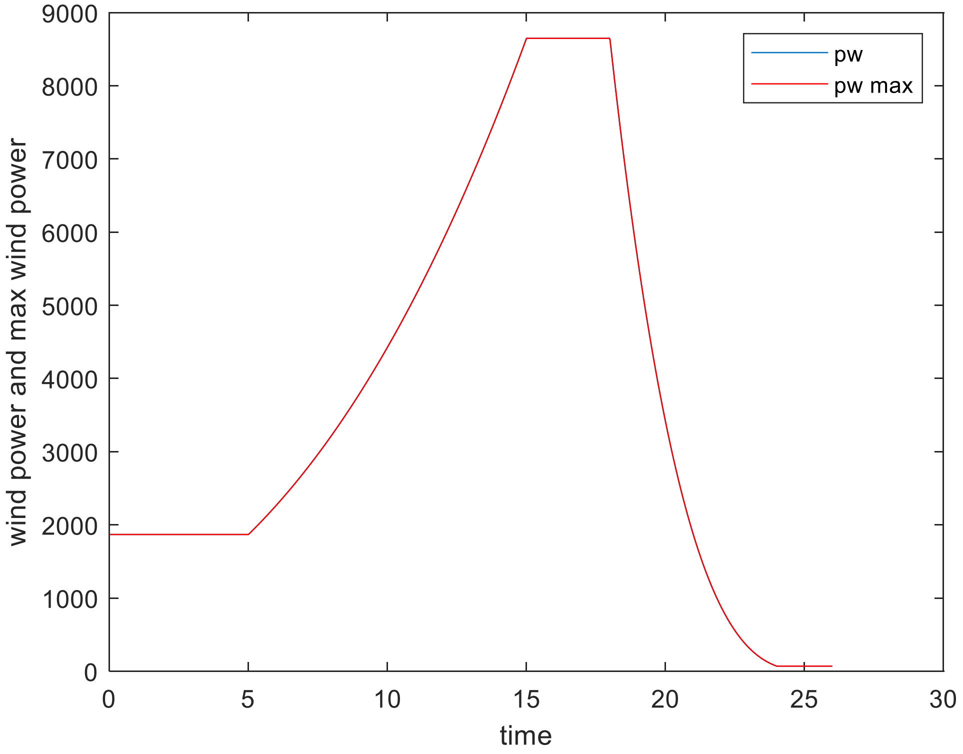

Figure III- 11 : Wind Power(P_w) and its maximum reference value (P_{wmax}) (W).

3.5 Control strategies applied to GSC

The main goal of controlling the GSC is to ensure the following objectives:

a) Guarantying a smooth DC voltage of the DC bus in order to ensure a balance power of all components of the wind system;

b) A decoupled control of the active and reactive power flow between the network and the DC bus with a desired power factor.

In this section, we will establish the control scheme of the GSC. To do this, a PI regulator will be synthesized to control the DC bus voltage (V_{dc}) to its reference value (V_{dcref}). The active and reactive power circulating in the three-phase line, connecting the GSC and the network are expressed by:

$$P_g = \frac{3}{2}(v_{dg} i_{dg} + v_{qg} i_{qg}) \qquad \text{(III-12)}$$

$$Q_g = \frac{3}{2}(v_{qg} i_{dg} - v_{dg} i_{qg})$$

The orientation of the network voltage on the *d*-axis leads to:

$$v_{dg} = u_s \tag{III-13}$$

$$v_{qg} = 0 \tag{III-14}$$

Therefore, the expressions giving the active and reactive power (equation) are simplified and become:

$$P_g = \frac{3}{2} u_s i_{dg} \tag{III-15}$$

$$Q_g = -\frac{3}{2} u_s i_{qg} \tag{III-16}$$

From equation (III-12), one can remark that the active power (P_g) can be controlled, at its reference value (P_{gref}), by acting on the direct component (i_{dg}) of the line current and consequently the set point for this current is expressed by:

$$i_{dgref} = \frac{2}{3u_s} P_{gref} \tag{III-17}$$

Also, from equation (III-13), one can remark that the reactive power (Q_g) can be regulated to its reference value (Q_{gref}) by the adjusting quadrature component (i_{qg}) of the line current. From where, we can establish the reference current expression:

$$i_{qgref} = -\frac{2}{3u_s} Q_{gref} \tag{III-18}$$

Elsewhere, the active power at the DC bus side is equal to the active power exchanged between the GSC and the network with negligible losses and one can write:

$$v_{dc} i_{red} = \frac{3}{2} u_s i_{dg} = v_{dc} i_{ond} \tag{III-19}$$

Where: i_{red} is the average value of the modulated current on the GSC side.

i_{ond} Is the average value of the modulated current on the MSC side.

From equation (III-19), one can see that the DC bus voltage (v_{dc}) can be controlled by acting on the current component (i_{dg}). A PI controller combined with hysteresis current controller is used to control the GSC to ensure all the cited performances in closed loop.

The closed loop scheme of the PI controller applied to the DC voltage control is depicted in the following figure:

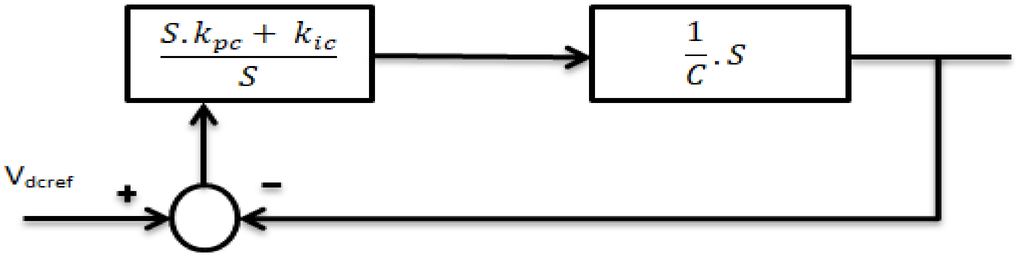

Figure III-12 : Closed loop of PI controller applied to the DC voltage.

Noting that, the PI parameters calculation is established in the same manner as in the MSC speed control described previously. Finally, the global scheme control of the DC voltage and the power factor is presented in the following figure:

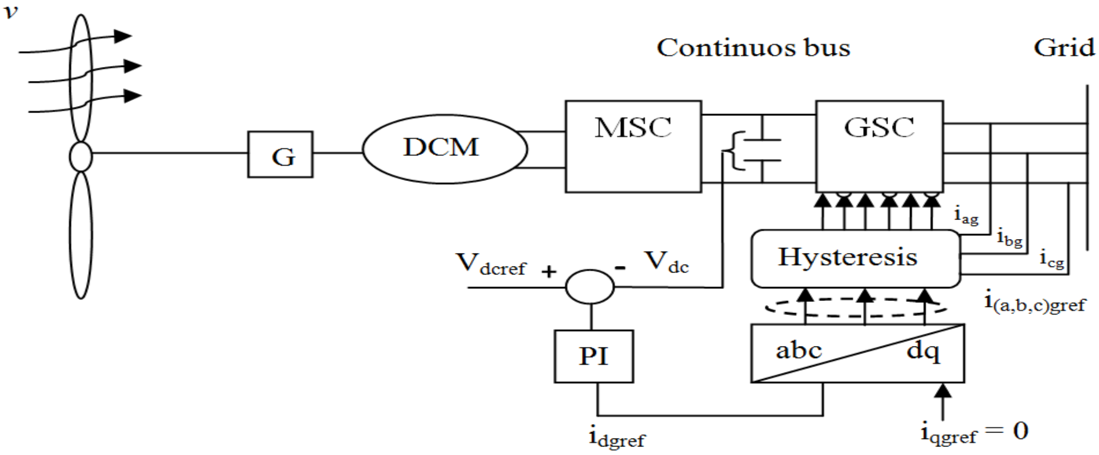

Figure III- 13 : Structure of the GSC control for DC voltage regulation and power factor correction.

Noting that, to achieve a unity power factor at the grid side, the injected reactive power reference is taken equal to zero. According to equation (III-18), to ensure a reactive power nil, the quadrature command current must be taken (i_{qgref}=0) (see Figure III-13).

3.6 Mechanical load control

As has mentioned previously, the mechanical load considered in this work is a DC machine driven by an H-Bridge converter. Also, a PI controller combined with hysteresis current controller is applied to regulate its speed to a desired value. The PI parameters sizing is achieving in the same manner as in the DC voltage and MSC regulation. Noting that the desired machine speed is fixed to 120 rd/s with a load torque of (cr=5N.m) which is applied at *t=0s*.

The obtained simulation results are presented in the figures (III- (14-16)):

From figure (III-14), one can note that the DC bus voltage (V_{dc}) is regulated practically to its reference (V_{dcref}=700V) with some fluctuations which are due to the different loads perturbations.

The zoom of the phase voltage (*Va*) and its corresponding current (i_a) shows that and after powering the load (mechanical load), the active power surplus is injected in the grid. Is negative which means that the wind system injects active power to the grid after powering the load (See figure III-16)).

For the second stage when the wind speed slows down to 2m/s from t=24s) (see figure III-6) , so, the zoom of the phase voltage (*Va*) and corresponding current (i_a) indicate that the produced wind power is not enough to satisfy the mechanical load power to operate at the desired speed with load required torque. So, the deficit of power is extracted from the grid to ensure the needed mechanical load power.

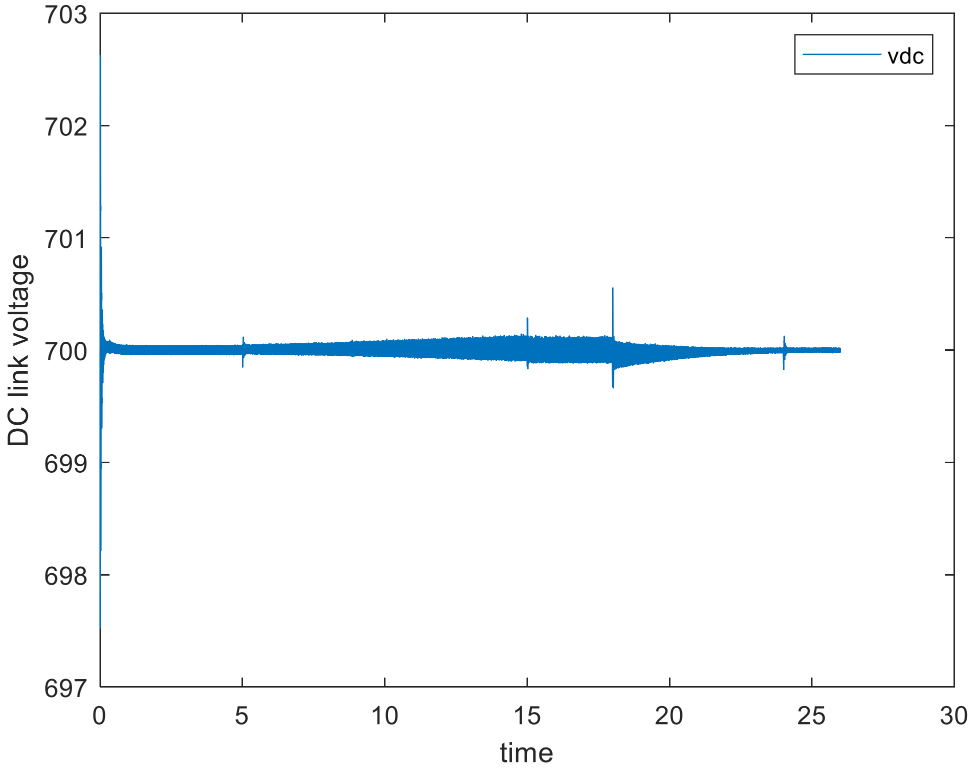

Figure III- 14 : DC bus voltage rate (*Vdc*) (V).

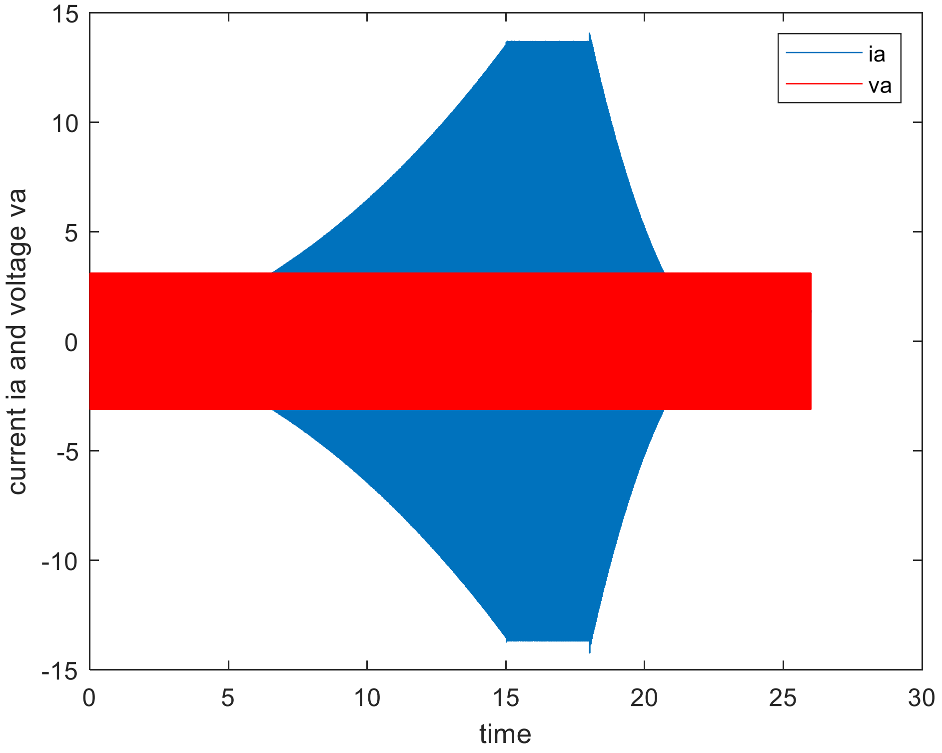

Figure III- 15 :Voltage $V_a(V)/100$ and current (i_a) of phase (a).

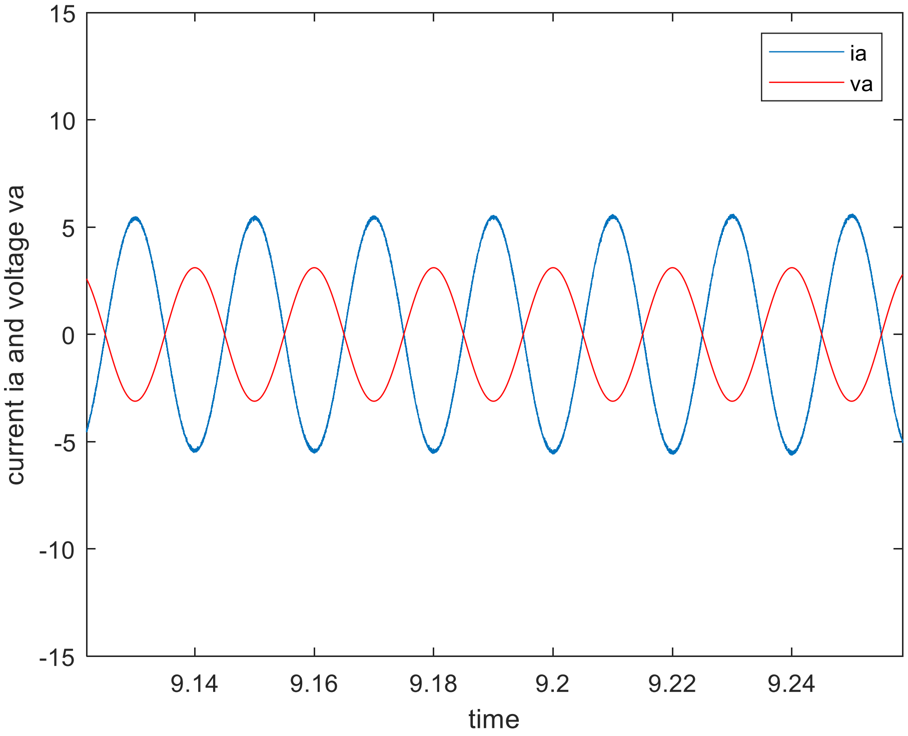

Figure III- 16 :Zoom voltage (V_a)/100) (V)and current (i_a) (A) of phase (a) in the case of enough wind power.

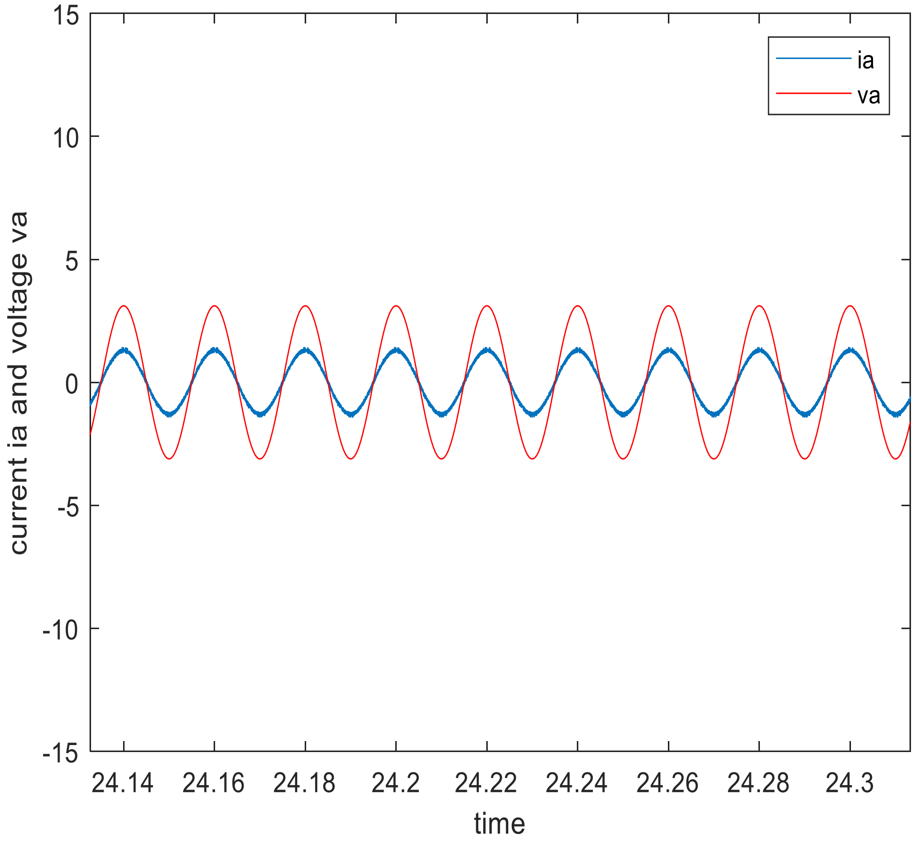

Figure III- 17: Zoom voltage ((V_a)/100) (V) and current (i_a) (A) of phase (a) in the case of not enough wind power.

The two following figures present the speed of the DC machine and its current. As you can observe that machine is regulated to its reference value of 120 rd/s (Figure III-18). And the machine draws a current of 2.74A in order to satisfy the load torque of 5N.m (Figure III-19). It is powered from the wind turbine and in the absence of sufficient wind power it powered from the grid through the continuous bus.

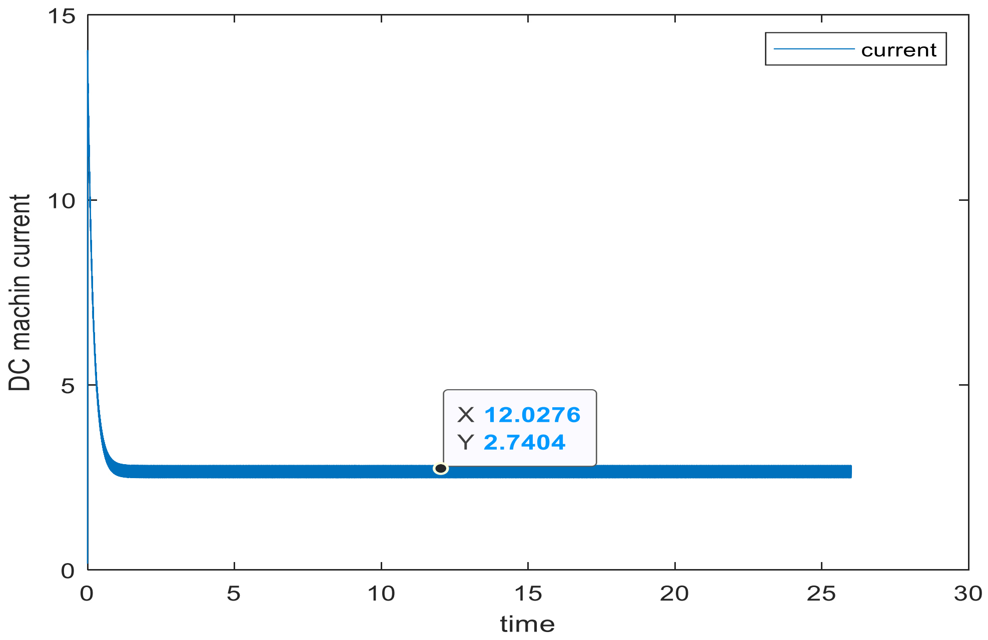

Figure III- 18: DC-machine curent (A).

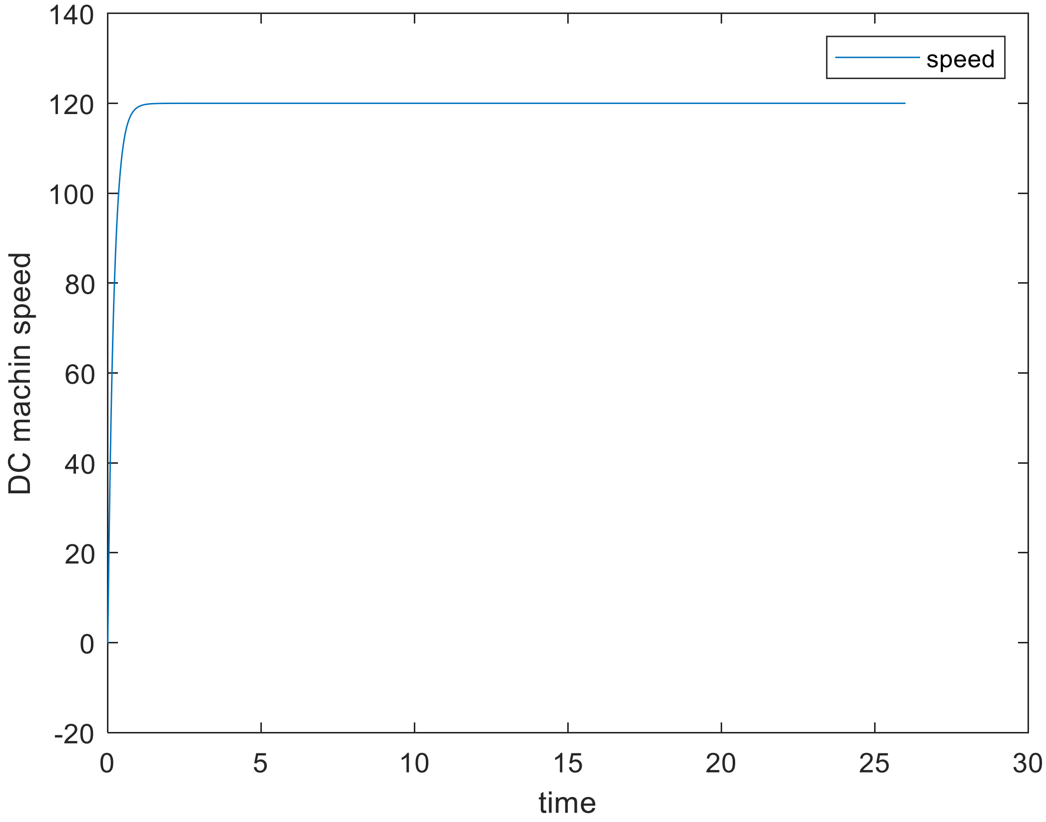

Figure III- 19: DC-machine speed (rd/s).

3.7 System power balance and losses calculation

The system losses are divided in two forms:

- Joule losses in resistors;
- Friction losses in the mechanical part of the system.

These total system losses are calculated as follows:

$$Perts = losses = R_a i_G{}^2 + R_a i_M{}^2 + 3R_r i_{eff}{}^2 + f_1 \omega_G{}^2 + f_2 \omega_M{}^2 \quad \text{(III.20)}$$

Where, R_a is the DC machine and the DC generator resistor (Ω);

R_r is the three phase line resistor (Ω);

$f_1$and f_2 are the friction of the DC machine and the DC generator (Ns/m);

i_{eff} is the rms value of the three phase current flowing in the line between the GSC and the grid (A);

i_G and i_M are the current of the DC machine and the DC generator (A);

ω_G and ω_M are the DC generator speed and the DC machine speed (rd/s).

Since the efficiency of the system is usually bellow unity, the produced active power at the grid side is equal the produced wind power minus the losses and one can write:

$$P_g = -(P_w - losses) \quad \text{(III.21)}$$

If $P_w$is greater than losses, P_g is negative which means that a power surplus in wind power which is injected in the grid. But, if P_w is less than *losses*, P_g is positive which means that the wind power is not enough to satisfy all losses and the needed power to supply the mechanical load is extracted from the grid.

The following figure shows the active power (P_g) (W) and $(-(P_w\text{-}losses))$(W). From the figure, one can note the two powers are identical.

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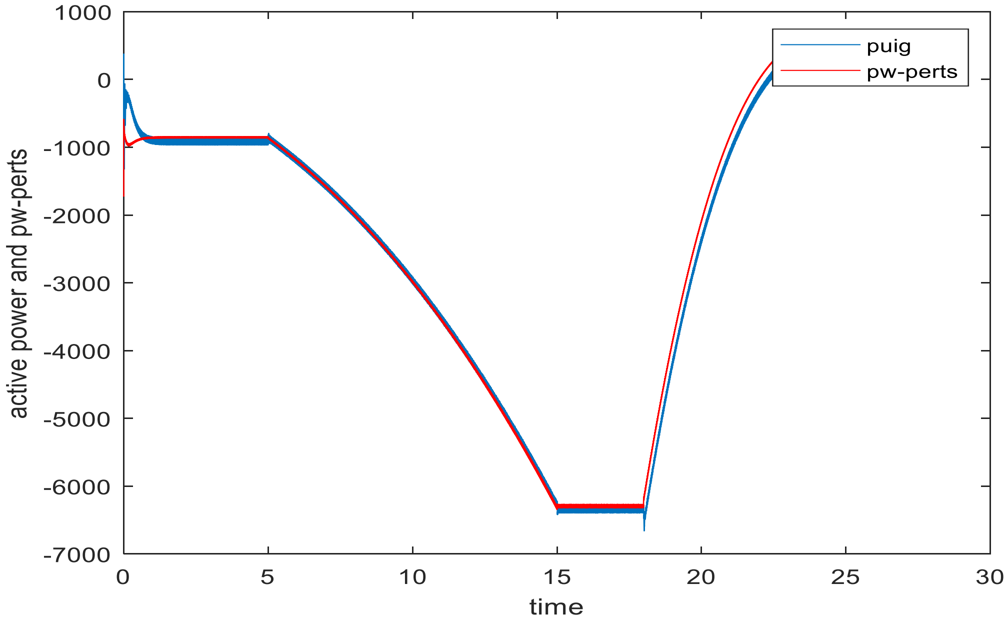

Figure III- 20: Active power (pg) and turbine power minues losses (-(pw-perts))(W).

The following figure shows the grid active power (P_g) and reactive power (Q_g). From the figure, one can remark, the reactive power (Q_g) is equal to zero in order to ensure a unity power factor at the gird side. From (*t=0s to 24s*), the active power is negative which means that is injected in the grid (case of wind power surplus). But for (t>24s) (wind speed is falling) (see Figure III-8), the active power is positive which means that is extracted from the grid to satisfy the needed power for different load and losses (case of insufficiency wind power).

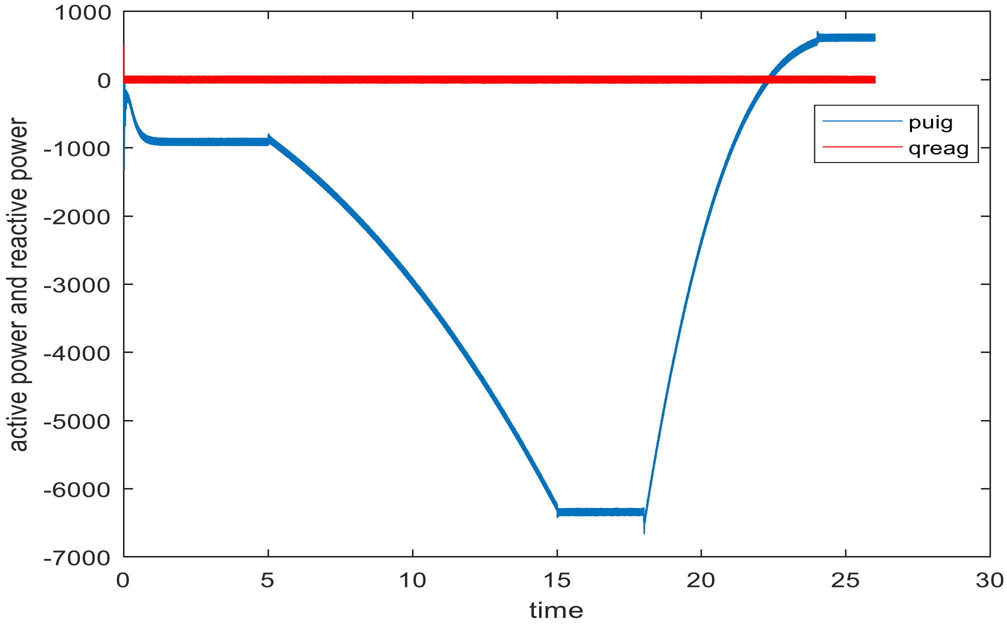

Figure III-21 :Grid active power P_g (W) reactive power (Q_g) (VAr).

3.8 CONCLUSION

This chapter has been devoted mainly to the control the converters (MSC and GSC) of the wind power system to satisfy the desired performances in closed loop. Indeed, the DC-generator has been controlled by a simple PI regulator to ensure operation in MPPT mode.Good dynamics responses have been obtained which proved the MPPT operating mode of the system.

Another PI controller has been applied to the GSC in order to ensure a smooth DC voltage with a unity power factor at the grid side. In fact, the DC voltage followed practically its reference value and a nil reactive power is injected in the grid which means that a unity power factor is achieved.

The speed of the loaded DC machine followed its reference value perfectly by using also a linear PI controller. From the simulation results, it has been proved that the produced active power is positive in the case of wind power surplus and positive in the case of wind power deficit.

General conclusion

The main goal of this thesis was to study and control a grid connected wind energy conversion system based on a DC generator and powering a mechanical load formed by a DC machine. In fact, after a general description of some wind turbines based on different generators. Since wind turbine based on DC generator has not been considered in any work yet in the literature, we have proposed a novel structure for this purpose. The wind system components modelling have been considered in the second chapter. Indeed, sample Statics and dynamics models are obtained. Three PI regulators are sized for controlling the system to satisfy the closed loop performances. In fact, the MPPT is successfully achieved through the H-bridge control and smooth DC voltage is guaranteed with a unity power factor through the GSC control also. The performances of a mechanical load are achieved (speed regulation with a load torque through the control of also an H-Bridge chopper. Other important thing concerning the produced grid active power, which is negative and injected in the grid in the case of wind power surplus and positive and extracted from the grid in the case of wind power deficit.

As perspectives, in order to enrich this work in the future, some perspectives are advanced:

- Using others controllers such (fuzzy logic, sliding mode,);

- Working the system with a unity power factor which is not nil;

- Ensure some ancillary servicessuch (active filtering, reactive power compensation, continuity of service in the event of a voltage dip;

- Adding others systems to buildan hybrid energy system.

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