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Title: Fuzzy Logic – based Hill Climbing MPPT For Wind Driven Permanent Synchronous Generator

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Dedication

To my dear parents who have always supported me and oriented me towards the good. For their help to follow my studies, their encouragement, their prayers and sacrifices, without forgetting my sister and my brothers to whom I wish a good success in their studies and work.

To my supervisor Pr. KHALDOUN AISSA and all the teachers and workers of INELEC.

To all those who helped me throughout my university life, without
forgetting my dear friends.

To all those who are dear to me.

lotfi

Abstract

Wind power has become a rapidly growing technology as a kind of renewable energy resources. It plays a more and more important role with the increasing demand on energy every day. Unlike fossil fuel power sources, with the fact that it emits no air pollution or greenhouse gas, also its ability to generate high amount of power with no fuel consumption, therefore it is becoming much more reliable and promising to be number one source for clean energy in the very near future.

Research of Wind Energy Conversion Systems (WECS) has gained great interest in the recent years to improve its behavior and response. One of the most important aspects is the Maximum Power Point Tracking (MPPT). The latter allows extracting the maximum power at the different wind speeds and therefore increasing the efficiency of the Variable-Speed Wind Turbine system when the wind speed is below the rated speed. Fuzzy sets are proposed in the present work to design the Maximum Power Point Controller. Simulation using Matlab /Simulink have shown that the investigated controller is fast and accurate.

Acknowledgement

In the name of Allah, the Most Gracious and the Most Merciful.

All praises to Allah and His blessing for the completion of this thesis. I thank God for all the opportunities, trials and strength that have been showered on me to finish writing the thesis. I experienced so much during this process, not only from the academic aspect but also from the aspect of personality. My humblest gratitude to the holy Prophet Muhammad (Peace be upon him) whose way of life has been a continuous guidance for me.

First and foremost, we would like to sincerely thank our supervisor **Prof**. **Aissa Kheldoun** for his guidance, understanding, patience, and most importantly, he has provided positive encouragement and a warm spirit to finish this thesis. It has been a great pleasure and honor to have him as a supervisor.

Our deepest gratitude goes to all of our family members. It would not be possible to write this thesis without the support from them

We offer our special thanks our friend and the most for **Dali Sid Ali** ,and also our friend **Bentayeb Yazid** for their motivation and their sincere help during our studies.

May God shower the above cited personalities with success and honor in their life..

Table of Contents

List of Tables

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List of Figures

Abbreviations

RES	Renewable Energy Sources
WECS	Wind Energy Conversion System
AC	Alternative Current
PMSG	Permanent Magentas Synchronous Generator
MPPT	Maximum Power Point Trucker
PWM	Pulse Width Modulation
MPP	Maximum Power Point
DC	Direct Current

General Introduction

Modern Electrical power systems are facing many challenges in development and expansion. These are no longer limited in technical issues, economic, or financial in nature but are environmental and social. Climate change and sustainable development are major challenges of the 21st century, with extraordinary implications for energy and environmental security[1].

Providing energy for a community, in a sustainable manner, nowadays has become a more and more important issue as we face global warming and climate change realities. Power generation engineers and designers have a responsibility to improve techniques of energy conversion in order to reduce emissions of CO2 and NOx, which are believed to be a source of environmental degradation. Harnessing renewable energy sources which are abundantly available in nature provides an opportunity to produce energy in an environmentally friendly way. Renewable energy resources like wind, solar, hydropower, biomass and geothermal energy have the potential to overcome these difficulties.

Advantage of renewable energy

Renewable energies are clean energy sources that have a much lower environmental impact than traditional energy technologies and will never run out. Conventional sources of energy are limited and one day they will run out because their primary energy sources are continuously depleting.

Another benefit of using renewable resources is that they are spread over a wide geographic area, ensuring that developing regions have long-term access to electricity generation at stable costs. The heat from the sun also drives the winds, whose energy is recorded by wind turbines. Then the winds and the heat of the sun evaporate the water. When this water vapor turns into rain or snow and flows downhill into rivers or streams, its energy can be obtained with the help of hydropower plants. Together with rain and snow, sunlight makes plants grow. The organic matter that these plants are made of is called biomass. Biomass can be used to generate electricity. The use of biomass for any of these purposes is known as bio energy.

Not all renewable energy resources come from the sun. Geothermal energy taps the Earth's internal heat for a variety of uses, including electric power production, and the heating and cooling of buildings. And the energy of the ocean's tides come from the gravitational pull of the moon and the sun upon the Earth. In fact, ocean energy comes from a number of sources. In addition to tidal energy, there's the energy of the ocean's waves, which are driven by both the tides and the winds. The sun also warms the surface of the ocean more than the ocean depths, creating a temperature difference that can be used as an energy source. All these forms of ocean energy can be used to produce electricity[8].

On the ground, the world is witnessing more deployment of solar and wind power plants. As a result, traditional fossil fuel and nuclear power plants have become uncompetitive with respect to solar and wind energy sources when considering global worm issues and impact on human health. That is, from efficiency point of view, both solar photovoltaic and wind energy conversion system still suffering from low conversion efficiency.

Thesis's context and problem to be solved

Wind energy conversion system (WECS) is the association of wind turbine with an electric machine being used as converter of mechanical energy to electrical energy. Many electric generators are available for use, however, three-phase AC machines are the most encountered in such WECSs. Since last decade, much interest has been given to Permanent magnet synchronous generator which available from few watts at several Megawatts. The main advantage over the squirrel cage induction generator is the fact that there is no loss in the rotor which makes it more compact and better in terms of efficiency. However, this efficiency can be altered by the accuracy of the maximum power tracking controller. Given that the wind speed is variable, the MPPT controller must track the maximum power point rapidly and accurately. This project is intended to investigate the development of Maximum Power Point Tracking controller based on the fuzzy sets. To achieve this, the report is organized in three chapters.

- Chapter one presents the WECS, its main components and the different classification encountered of WECS.

- Chapter two is devoted to the modelling of the WECS using the PMSG. The conversion principle using wind turbine is firstly presented then the model of each component composing the WECS is outlined. The chapter is ended by the presentation of the design of the MPPT controller using fuzzy sets.
- Chapter three summarizes the results of simulation using MATLAB/Simulink software. Discussion of each component's result alone, wind turbine, generator, rectifier, boost chopper are provided too. A general conclusion is drawn at the end to summarize obtained results and work still to be done as further work.

Chapter 1

Wind Energy Conversion System

1.1 Introduction

Wind is the result of difference in atmospheric pressure from one region to another. This difference in pressure is caused by the fact that the earth surface is not uniformly heated up by the sun, and the earth is continuously revolving around itself and the sun. Wind energy is available in the form of Kinetic Energy of air.

Wind energy is the use of air flow through wind turbines to provide the mechanical power to turn electric generators and traditionally to do other work, like milling or pumping. Wind power, as an alternative to burning fossil fuels, is plentiful, renewable, widely distributed, and clean. Furthermore, it produces no greenhouse gas emissions during operation, consumes no water, and uses little land. The net effects on the environment are far less problematic than those of fossil fuel sources [1].

1.2 Historical overview

Wind energy was used for thousands of years to mill grain, pump water and sailing. With the development of electric power, wind power found new applications in lighting buildings remote from centrally-generated power. The first electricity-generating wind turbine was a battery charging machine installed in July 1887 by Scottish academic James Blyth to light his holiday home in Scotland. Some months later, American inventor Charles Brush built the first automatically operated wind turbine for electricity production in Cleveland, Ohio of about 12 kW dc. However, it was only since the 1980s that the technology has become sufficiently mature to produce electricity efficiently and reliably from the wind [2]. Over the last two decades, a variety of wind energy systems have been developed. Throughout the 20th century parallel paths developed small distributed wind plants suitable for farms or residences, and larger utility-scale wind generators that could be connected to electricity grids for remote use of power [3].

Wind energy is relatively clean and sustainable. It is one of the most promising and fastest growing energy resources in the world. Figure 1.1 shows the annual installed capacity of wind power worldwide and annual additions [4]. The wind industry achieved an average growth of around 20 to 25% from 2001 to 2009. This impressive growth has been encouraged by the continuous cost reduction in wind turbines, the governments motivating programs for wind power production, and the public demand for cleaner energy source [4].

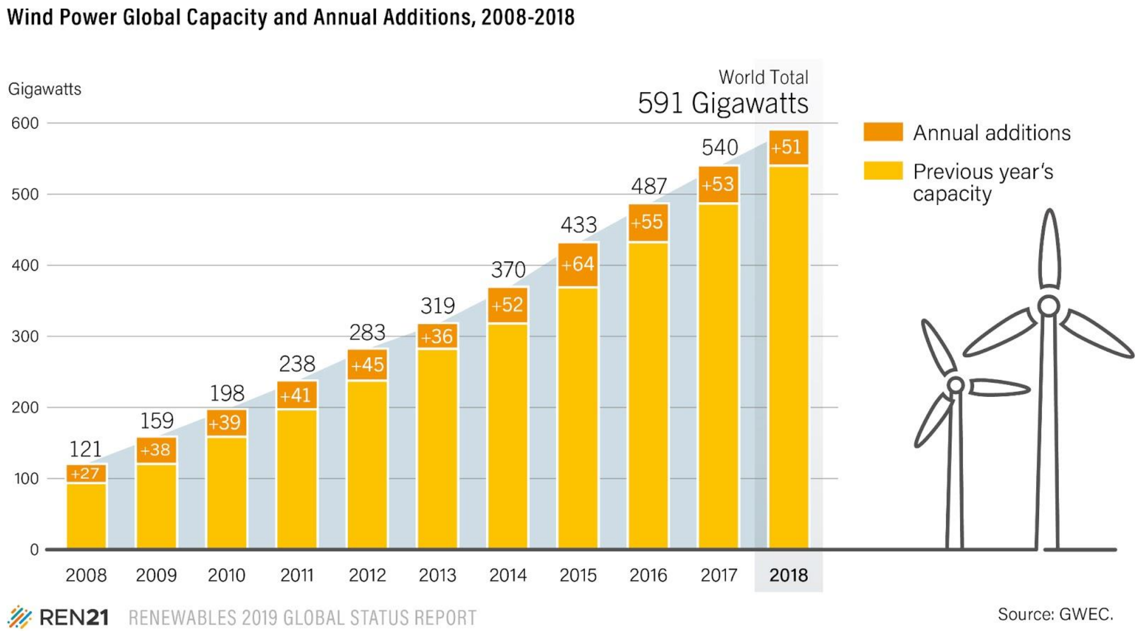

Figure 1.1 : global wind capacity and annual growth

1.2 Key components of WECS

1.2.1 Wind turbine

We have been harnessing the wind's energy for hundreds of years. From old Holland to farms in the United States, windmills have been used for pumping water or grinding grain. Today, the windmill's modern equivalent - a wind turbine - can use the wind's energy to generate electricity.

Wind turbines, like windmills, are mounted on a tower to capture the most energy. At 30 meters or more aboveground, they can take advantage of the faster and less turbulent wind. Turbines catch the wind's energy with their propeller-like blades. Usually, two or three blades are mounted on a shaft to form a rotor.

A blade acts much like an airplane wing. When the wind blows, a pocket of low-pressure air forms on the downwind side of the blade. The low-pressure air pocket then pulls the blade toward it, causing the rotor to turn. This is called lift. The force of the lift is actually much stronger than the wind's force against the front side of the blade, which is called drag. The combination of lift and drag causes the rotor to spin like a propeller, and the turning shaft spins a generator to make electricity.

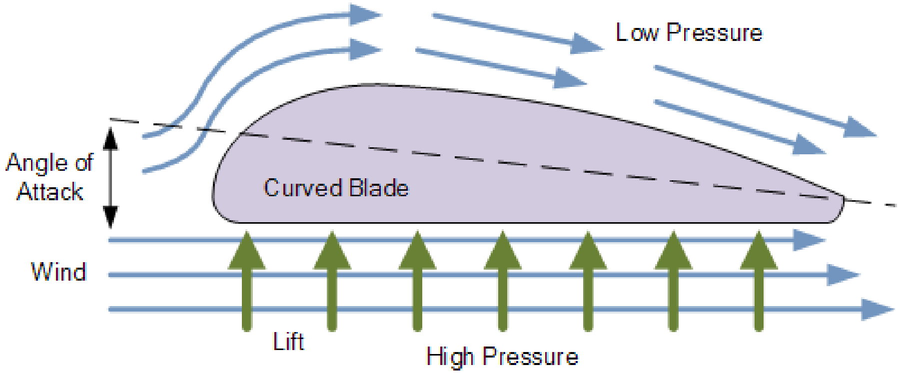

Figure 1. 2: Wind turbine blade design

1.2.2 Generator

Any type of electric generator can be connected with a wind turbine. However, the most employed electric machines with the wind turbine are Asynchronous (induction) generator and synchronous machine. Squirrel cage induction generator (SCIG) and wound rotor induction generator (WRIG) can be classified under Asynchronous generator type. Wound rotor generator (WRSG) and permanent magnet generator (PMSG) are types of synchronous generator.

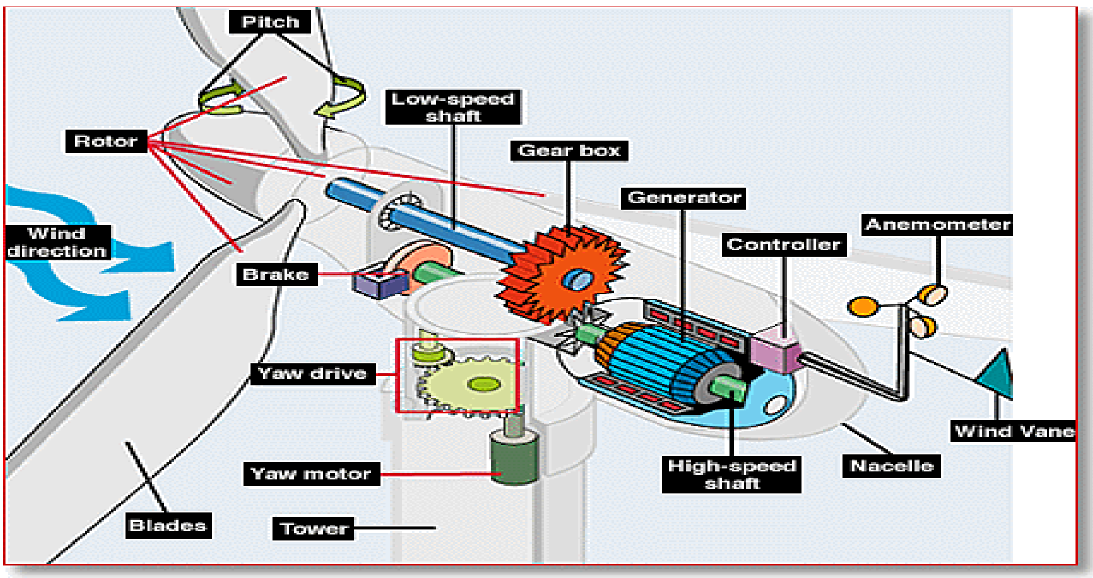

Figure 1. 3: Wind turbine diagram

Wind turbines can be used as stand-alone applications, or they can be connected to a utility power grid or even combined with a photovoltaic (solar cell) system. For utility-scale renewable sources using wind energy, a large number of wind turbines are usually built close together to form a wind farm. Several electricity providers today use wind plants to supply power to their customers [5].

1.2.3 Gearbox

Drive trains in wind energy conversion system commonly includes a gearbox which is used typically in the WT to transform slow speed, high torque of the rotor blades to the higher speed for the shaft of the electrical generator, since that increase in speed is needed to improve the efficiency of the EG that operates at high speed comparing to wind turbine rotors. Gearbox also used for supporting the heaviest component of the wind turbine. Gearbox failures are the most occurring faults in the wind energy conversion system which makes it a major drawback in the operation of wind turbines, especially for offshore wind turbines that are situated in harsh and less-accessible environments. Because of this, a new topology has become increasingly adopted in which they remove the gearbox, and connects the wind turbine's rotor directly to the shaft of a multi-poles generator.

1.3 Classification of Wind energy system

Wind energy systems can be classified classified as:

1.3.1 According to the size of generator:

(i) Small turbines (less than 2 kW): These may be used for remote applications, or at places requiring relatively low power.

(ii) Medium turbines (2 - 100 kW): These turbines may be used to supply less than 100 kW rated capacity to several residences or local use.

(iii) Large turbines (greater than 100 kW): They are used to generate power for distribution in central power grids, commonly known Distributed Generation.

1.3.2 According to the rotational speed of the aero-turbines

(i) Fixed Speed Operation: it consists of a conventional, directly grid coupled squirrel cage induction generator, which has some superior characteristics such as brushless and rugged construction, low cost, maintenance free, and operational simplicity. The slip and hence the rotor speed of a squirrel cage induction generator varies with the amount of power generated. These rotor speed variations are, however, very small, approximately 1 to 2 % of the rated speed. Therefore, this type of wind energy conversion system is normally referred to as a constant or fixed speed WTGS. The

advantage of a constant speed system is that it is relatively simple. However, constant speed turbines must be more mechanically robust than variable speed turbines. Because the rotor speed cannot be varied, fluctuations in wind speed translate directly into drive train torque fluctuations, causing higher structural loads than with variable speed operation. This partly cancels the cost reduction achieved by using a relatively cheap generating system.

(ii) Variable Speed Operation: The main advantage of variable speed operation is that more energy can be generated for a specific wind speed regime. Although the electrical efficiency decreases due to the losses in the power electronic converters that are essential for variable speed operation as shown in fig.1.4, the aerodynamic efficiency increases due to variable speed operation. The aerodynamic efficiency gain can exceed the electrical efficiency loss, resulting in a higher overall efficiency. In addition, the mechanical stress is less because the rotor acts as a flywheel (storing energy temporarily as a buffer), reducing the drive train torque variations. Noise problems are reduced as well because the turbine runs at low speed. The main drawback of variable speed generating systems is that they are more expensive.

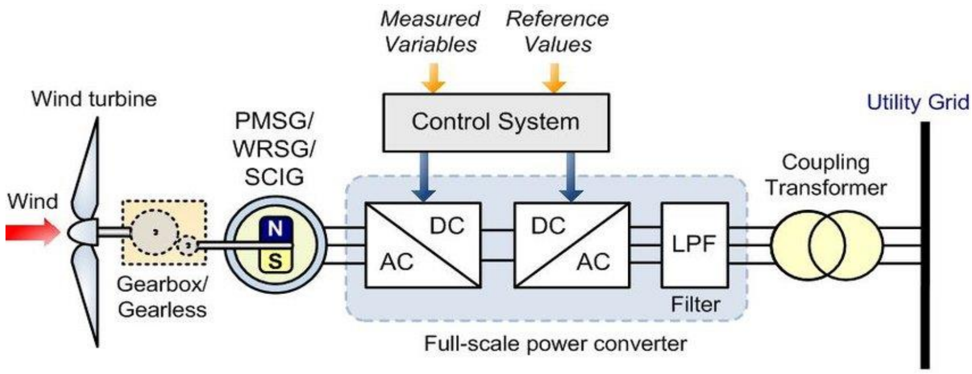

Figure 1.4: grid connected - variable speed WECS

1.3.3 According to the orientation of turbines

There are two types of wind turbines, horizontal-axis and vertical-axis turbines:

(i) Horizontal Axis Wind Turbine (HAWT): In horizontal axis wind turbines (HAWT), the axis of rotation is parallel to the direction of the wind, as shown in fig. 1.5.a). There may be many designs of horizontal axis wind mills. Depending upon the number of blades, these may be classified as single bladed, double bladed, three bladed, multi

bladed and bicycle bladed [1,6]. Depending upon the orientation of the blades with respect to wind direction these may be classified as up wind and down wind type. As the wind changes direction, all horizontal axis wind machines have some means for keeping the rotor into the wind, e.g. powered system. On smaller wind machines, such as the farm windmill, the tail vane keeps the rotor pointed into the wind, regardless of changes in wind direction. Both tail vanes and fan tails use forces in the wind itself to orient the rotor upwind of the tower.

(ii) Vertical Axis Wind Turbine (VAWT): In VAWT, the axis of rotation is perpendicular to the direction of the wind, as shown in fig. 1.5. b). These machines are also called cross wind axis machines. The main designs of vertical axis machines are the Savonious rotor and Darrieus rotor. The principal advantages of VAWT over conventional HAWT are that VAWT are omni-directional, i.e. they accept the wind from any direction. This simplifies their design and eliminates the problem imposed by gyroscopic forces on the rotor of conventional machines as the turbines yaw into the wind. The vertical axis rotation also permits mounting the generator and gear at the ground level [13]. On the negative side, the VAWT requires guy wires attached to the top for support, which may limit its application, particularly for of shore sites.

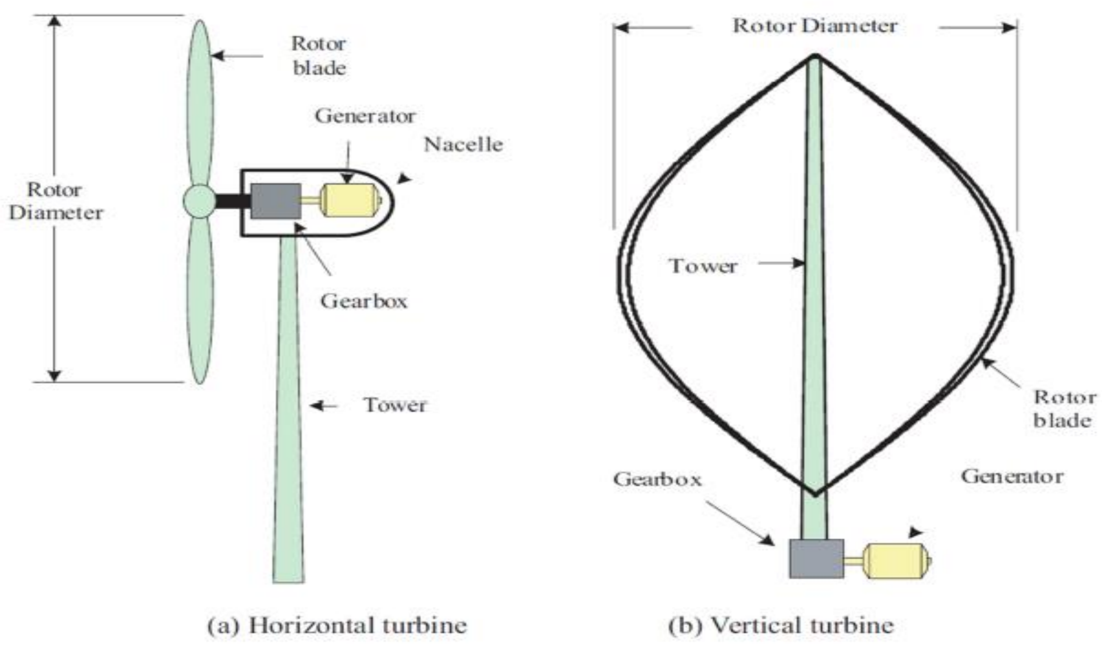

Figure 1.5: Horizontal axis and vertical axis wind turbine

1.4.4 According to the connection

There are two types of connections, grid connected system and stand-alone system

(i) *Stand-alone Wind energy systems:* the whole system is not not connected to the network (off-grid), see fig. 1.6. It needs a storage battery bank or a diesel generator which is involved in the system to make the energy available at low wind speeds or at days-of autonomy, sometimes called no-wind-days. When the wind speed is less than the cut-in speed or not high enough to turn the turbine blades, the storage system takes over and deliver the required energy.

(ii) Grid-connected Wind energy systems: the generator of this type is connected to public electricity network (on-grid) through power electric interface and a filter. Most of grid-connected WECS are done to the distribution system. Therefore, their connection require more complex design as to fulfill some connection standards.

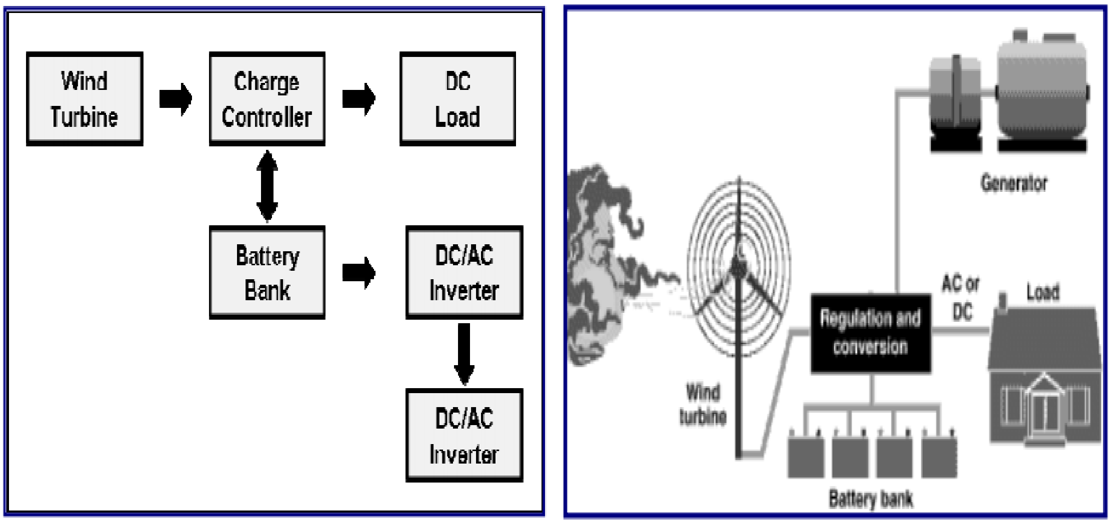

Figure 1.6: stand-alone wind energy systems

10 Conclusion

In this chapter we presented the wind energy conversion system, by giving a brief definition of its key components, namely generator, turbine and gearbox. The chapter has presented the different types of WECS classifications. Four classifications have been discussed: size, connection type, turbine orientation and finally to turbine rational speed. Finally, we have explained the power extraction from the wind using the WTG setting the ground for the next chapter that discusses the dynamic model of our WTG system.

2.1 Introduction

Every wind energy conversion system (WECS) essentially consists of three parts. Wind turbine, power generator and electronic power processing system. The latter is the most important part as its function allows extracting maximum power, and synchronisation with grid to which the system is connected. The objective of the present work is the implementation of maximum power extraction tracking controller. To this, this chapter is limited to the modelling of WECS components and the presentation of the maximum power tracking algorithm.

2.2. Wind energy conversion principle

The basic principle of the wind turbine is to convert the linear motion of the wind into rotational energy. This rotational energy is used to drive an electrical generator, which enables the kinetic energy of the wind to be converted into electrical energy. The kinetic energy available from the wind can be described as:

$$E_K = \frac{1}{2}\ m\,V_w^{\,2} = \frac{1}{2}\rho.A.d.V_w^{\,2} \tag{2.1}$$

The captured power of the wind (Pw) for a wind turbine is given by:

$$P_w = \frac{1}{2}\frac{m.V_w}{t} = \frac{1}{2}\frac{\rho.A.d.V_w^2}{t} = \frac{1}{2}\ \rho.A.d.V_w^{\,3} \tag{2.2}$$

Where:

ρ = air (wind) density,

A = rotor swept area (Area swept by the turbine),

d = radius of the swept area ,

D = thickness of the parcel (D = Vw * t),

m = mass of air = air density * volume = ρ*A*d, and

Vw = wind speed (m/s).

The mechanical power (Pm) generated by the wind turbine from captured power of thewind depends on the power coefficient (Cp) of the wind turbine. The physical meaning of the Cp curve is the ratio of the actual power delivered by the turbine and the theoreticalpower available in the wind. A turbine's efficiency, and thus power coefficient curve, is what differentiates one turbine from another. Eq. (2.3) expresses this relationship.

$$P_m = P_w . C_p(\Lambda,\beta) = \frac{1}{2}\rho . A . d . V_w^3 . C_p(\Lambda,\beta) \qquad (2.3)$$

Where

- Cp (λ, β) = power coefficient function,
- λ = the tip speed ratio (TSR), and
- β =pitch angle.

The coefficient of performance function Cp (λ, β) depends on two factors. The first factor is the Tip Speed Ratio (TSR) λ and the second is the pitch angle β. The wind turbine manufacturer usually provides this function (in the form of a curve), as it characterizes the efficiency of its wind turbines. If this curve is not provided, it can be obtained through performing field tests. The coefficient of performance can be evaluated by the following expression:

$$C_p(\Lambda,\beta) = \frac{Actual\_turbine\ \_power}{theoretical\_wind\_power} = \frac{P_m}{P_w} = \frac{P_m}{2.A.V_w^3} \qquad (2.4)$$

The tip speed ratio (TSR), λ, refers to the ratio of the turbine angular speed (ω) over the wind speed. The mathematical representation of the tip speed ratio is given by (2.5)

$$\lambda = \frac{\Delta\omega}{2.V_w} \qquad (2.5)$$

The pitch angle, β, on the other hand, refers to the angle by which the turbine blades arealigned with respect to its longitudinal axis. A typical Cp curve with a fixed pitch angle is illustrated by Figure 2.3

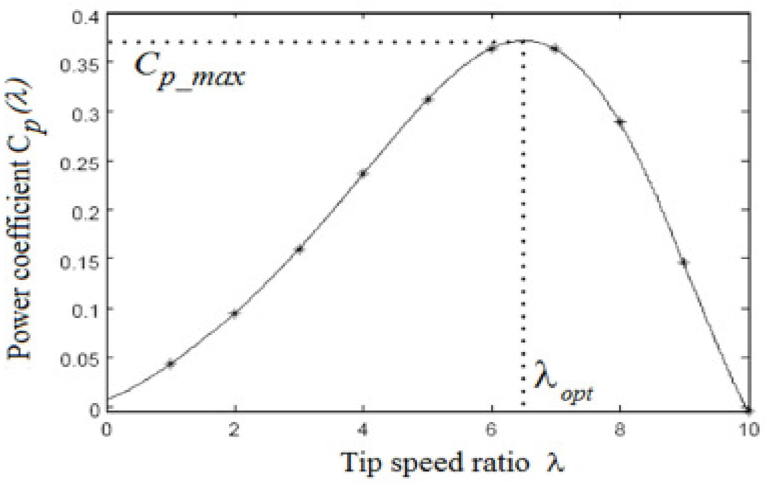

Figure2.3: Cp versus tip-speed ratio λ

Since the air density and rotor swept area can be considered constant, the power curves for each wind speed are only influenced by the Cp curve. Thus, as it can be seen in Figure 2.4 that the shape of the power characteristic is similar to the Cp curve in Figure 2.3.

Also from Figure 2.4, it should be noted that the point at which maximum power occurs for each wind speed is different and distinct .

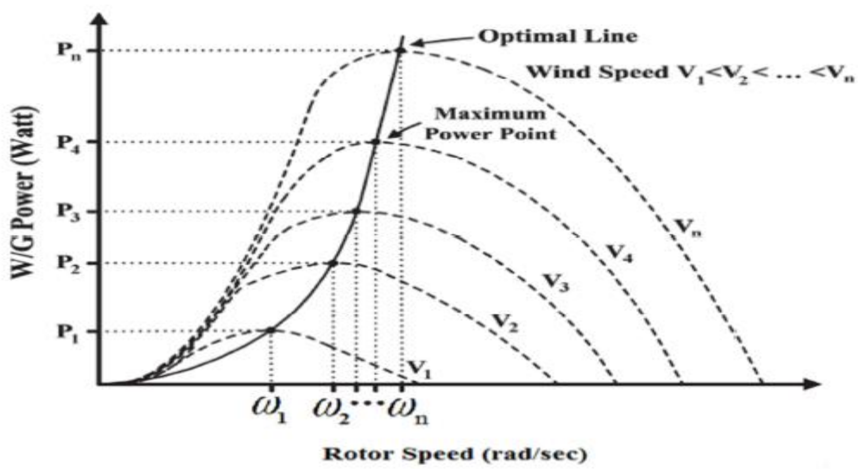

Figure 2.4: Power – rotor peed characteristics

The turbine mechanical torque is as follows

$$T_m = P_m \frac{d}{2.\lambda.V_w} \tag{2.6}$$

Where: d = turbine radius,

and V_w = is the wind velocity.

Equation above shows that the mechanical torque produced by the turbine is a function of mechanical power, tip speed ratio, gear ratio, turbine radius, and wind speed. By substitution we get:

$$T_m = \frac{1}{2}\rho.A\frac{d}{V_w}.C_p(\Lambda,\beta) \quad (2.7)$$

After simplification, eq. (2.7) becomes:

$$T_m = \frac{\rho.A.V_w.C_p(\Lambda,\beta)}{2.\omega} \quad (2.8)$$

From equation of Tm it can be seen that the mechanical torque available from the wind turbine is the same as the classical physical equation of torque (tm) and power (Pm).

Where:

Pm = Tm * angular velocity (ω).

Like the power characteristic, it should also be noticed that the shape of the torque curve is characterized by the power coefficient (Cp). As a result, the peak torque will also correspond to a particular rotor speed.

Turbine parameters	**value**
Turbine rated power (MW)	2
Number of blades	3
Blade diameter (m)	80
Rated wind speed (m/s)	14
air (wind) density (kg/m3)	1.22

Table 1: Wind turbine parameters

2.3Generator Model

The conversion of rotational mechanical energy to electric energy is performed by the generator. Different generator types have been used in wind energy systems over the years. These include the squirrel cage induction generator (SCIG), doubly fed induction generator (DFIG), and synchronous generator (SG) (wound rotor and permanent magnet) with power ratings varying from a few kilowatts to several megawatts. The advantages and disadvantages of each type will be presented bellow in table 2

Type	Advantages	Disadvantages
Induction Generator (SCIG-Fixed Speed)	• Simple and low cost. • Simple and minimized maintenance cost.	• No control on real and reactive power • Less optimum power extraction capability • Poor power factor • High mechanical stress on turbine mechanical components
Synchronous Generator	• Full speed range • Possible to avoid gearbox. • Complete control of active and reactive power.	• Small converter for field • Full scale power converter. • Limited fault ride through capability. • Additional cost of power electronics
Permanent Magnet Synchronous Generator	• Full speed range • Possible to avoid gearbox. • Complete control of active and reactive power • Brushless (low maintenance) • No power converter for field.	• Full scale power converter • Multi-pole generator (big and heavy) • Permanent magnets needed. • Limited fault ride through capability. • Additional cost of power electronics

	• High energy efficiency.	
Doubly-Fed Induction Generator	• Inexpensive small capacity PWM Inverter • Complete control of active and reactive power. • Smooth grid connection	• Need slip rings • Need gearbox. • Limited fault ride-through capability. • Regular maintenance of slip ring and gearbox
Squirrel cage Induction Generator	• Full speed range • No brushes on the generator • Complete control of active and reactive power	• Full scale power converter • Need gearbox.

Table 2 : advantages and disadvantages of each type of generators

2.5.1 Permanent magnet synchronous generators (PMSG)

We choose the PMSG from all the generators that are used in wind turbines because it is stable and safe in normal operation and does not require an additional DC power supply for the excitation circuit (winding). The dc excitation system is replace by permanent magnet behind which it is named PMSG. Originally it was used for small and medium-sized outputs, but since last decade PMSGs are also used for higher outputs (due to their advantages already mentioned)[6].

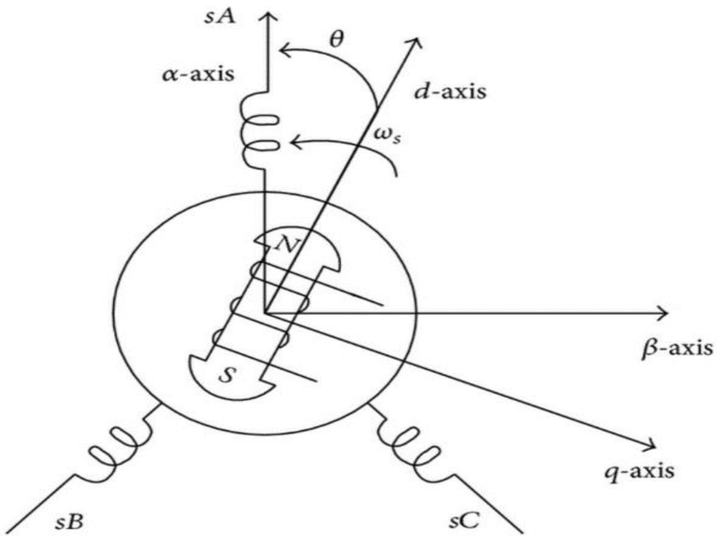

Figure Erreur ! Il n'y a pas de texte répondant à ce style dans ce document.**.5:** The Configuration of the Winding and PM in the PMSG**.**

2.5.2Modeling of PMSG

Before developing the mathematical model of the PMSG, several important assumptions need to be made:

(1) the damping effect in the magnets and in the rotor are negligible.

(2) the magnetic saturation effects are neglected.

(3) the eddy current and hysteresis losses are neglected.

(4) the back electromotive force (EMF) induced in the stator windings are sinusoidal.

For simplicity, all the equations of PMSGs are expressed in motor (consumer/load) notation, that is, negative current will be prevailing when the model refers to a generator. Negative current means that at the positive polarity of the terminal of a device the current is out of that terminal.

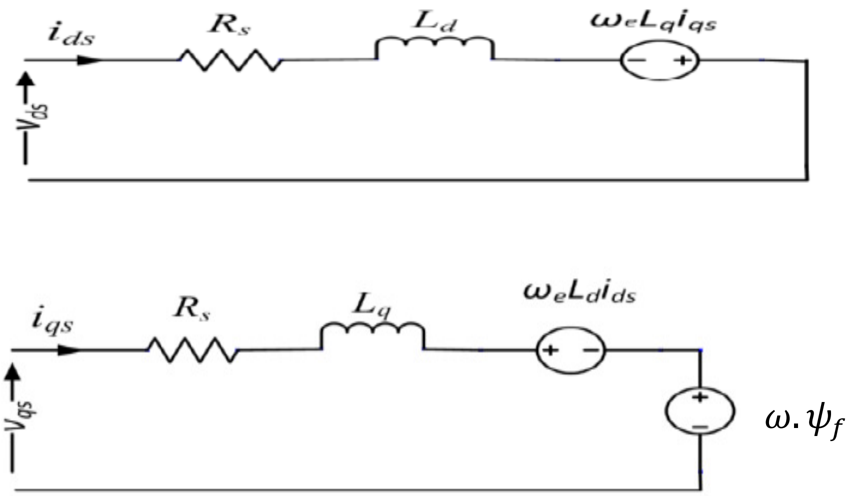

Figure 2.6 Equivalent Circuit of PMSG in d-q reference frame

The voltage equations of a permanent magnet synchronous generator in the dq reference can be derived from fig. 2.6. Considering generation mode (current out of the circuit) and applying KVL to both circuits of fig.2.6 give the following equations:

$$V_{qs} = -R_s i_{qs} + \omega \ \psi_{ds} + \frac{d\psi_{qs}}{dt} \quad (2.9)$$

$$V_{ds} = -R_s i_{ds} - \omega \ \psi_{qs} + \frac{d\psi_{ds}}{dt} \quad (2.10)$$

Where:

V is the voltage,

i the current,

ψ the flux linkage,

R_s the resistance,

ω the angular velocity of the rotor.

The subscripts ‘d’ and ‘q’ are the abbreviation of direct and quadratic components, rspectively

The flux linkages are given by:

$$\psi_{qs} = L_q i_{qs} = (L_{qm} + L_{\sigma s}) i_{qs} \quad (2.11)$$

$$\psi_{ds} = L_d i_{ds} + \psi_f = (L_{dm} + L_{\sigma s}) i_{ds} + \psi_f \quad (2.12)$$

Where:

ψ_f is the flux produced by the permanent magnet.

By substituting flux linkages Eq (2.9), (2.10) in system of Eq (2.10), (2.12) the voltage current relationship can be obtained:

$$\mathrm{V_{qs}} = -R_s i_{qs} - \frac{L_q d(i_{qs})}{dt} - \omega \ \ L_d i_{qs} + \psi_d \quad (2.13)$$

$$\mathrm{V_{ds}} = -R_s i_{ds} - \frac{L_d d(i_{ds})}{dt} - \omega \ \ L_q i_{qs} \quad (2.14)$$

The mechanical Torque equation is:

$$\mathrm{T_m} = T_{em} + J\frac{d\omega_r}{dt} + F\omega_r \ldots \quad (2.15)$$

$$T_{em} = \frac{3p}{2}(i_{qs}\lambda_r - (L_d - L_q) i_{ds} i_{qs}) \quad (2.16)$$

Where:

J: Inertia moment of the turbine,

F: Friction coefficient,

T_{em}: generator's electromagnetic torque.

Solving for the rotor mechanical speed with $\omega = \omega_r(\frac{2}{P})$. In the above equations ω_r is the rotor mechanical speed where as ω is the rotor electrical speed, and the

The PMSG presented in this thesis is a 2MW direct driven generator, with rated volt690V. The parameters of the PMSG are listed in Table 3 [7]. equation of the position is given as: $\theta = \theta_r(\frac{2}{P})$.

PMSG parameters	**Value**
Rated Power (MW)	2
Rated line to line Voltage (V)	690
Rated phase Voltage (V)	400

Rated Stator Current A (Rms)	1867.76
Rated Stator Frequency (Hz)	11.25
Number of Pole pairs	26
Stator Winding resistance R_s (mΩ)	0.821
d-axis Synchronous Inductance L_d (mH)	1.5731
q-axis Synchronous Inductance L_q (mH)	5731
Flux Leakage (V.s)	6.5
Rated Rotor Speed rpm	20.5

Table 3: PMSG parameters

2.6 Reference frame transformation

The reference frame theory can be used to simplify the analysis of electric machines and also to facilitate the simulation and digital implementation of control schemes in wind energy conversion systems. A number of reference frames have been proposed over the years, of which the three-phase stationary frame (also known as *abc* frame),the two-phase stationary frame *(aß* frame), and the synchronous frame *(dq* rotating frame) are most commonly used [7].

The transformation of variables between these reference frames is presented below :

- ***abc/dq* Reference Frame Transformation**

Consider generic three-phase electrical variables, *xa, xb,* and *xc,* which can represent either voltage, current, or flux linkage. The three-phase variables can be represented by a space vector *x* in a three-phase *(abc)* stationary reference frame (coordinate system)[7]. The relationship between the space
vector and its three-phase variables is illustrated below:

$$\begin{bmatrix} x_d \\ x_q \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos\theta & \cos(\theta - 2\pi/3) & \cos(\theta - 4\pi/3) \\ -\sin\theta & -\sin(\theta - 2\pi/3) & -\sin(\theta - 4\pi/3) \end{bmatrix} \cdot \begin{bmatrix} x_a \\ x_b \\ x_c \end{bmatrix}$$

- ***dq/abc* Reference Frame Transformation**

Also we can get the inverse which is used in the transform electric quantities from dq to abc reference frame, it is give, by the following :

$$\begin{bmatrix} x_a \\ x_b \\ x_c \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta \\ \cos(\theta - 2\pi/3) & -\sin(\theta - 2\pi/3) \\ \cos(\theta - 4\pi/3) & -\sin(\theta - 4\pi/3) \end{bmatrix} \cdot \begin{bmatrix} x_d \\ x_q \end{bmatrix}$$

2.7.Three-phase diode bridge rectifier

To supply the intermediate circuit, the PMSG should be connected to a rectifier that converts the AC voltage into DC voltage. Six diodes are used for an uncontrolled three-phase bridge rectifier. The uncontrolled three-phase bridge rectifier is the simplest, cheapest and most robust topology used in power electronics applications. The main disadvantage of this diode rectifier is its inability to operate in the bidirectional power flow.

IfV_m is the peak value of the phase voltage, the average output voltage is given by:

$$V_{d,out} = \frac{2}{2\pi/6}\int_0^{\pi/6} \sqrt{3}\,V_m \cos\omega t \, d(\omega t) \qquad (2.16)$$

Then the output dc voltage from bridge rectifier (if there is no capacitor)can be obtained from the previous equations where the overlap due to the internal inductance of PMSG is ignored [18].

$$V_{d,out} = \frac{3\sqrt{2}\,V_{LL}}{\pi} \qquad (2.17)$$

Where;

$V_{d,out}$: output dc voltage of the rectifier,

V_{ll}: line to line voltage.

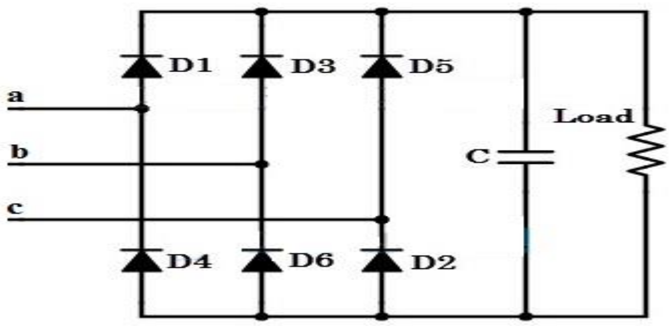

Figure 2.6: three phase uncontrolled rectifier

2.8 RC parallel dipole

The variation of the voltage across the dipole is governed by equation, fig. 2.7.a)

$$i(t)=C\,dv(t)/dt + v(t)/R \tag{2.18}$$

$$\Rightarrow v(t) = \frac{1}{C}\int (i(t) - v(t)/R \tag{2.19}$$

The RC parallel dipole is modelled by the scheme illustrated in figure bellow

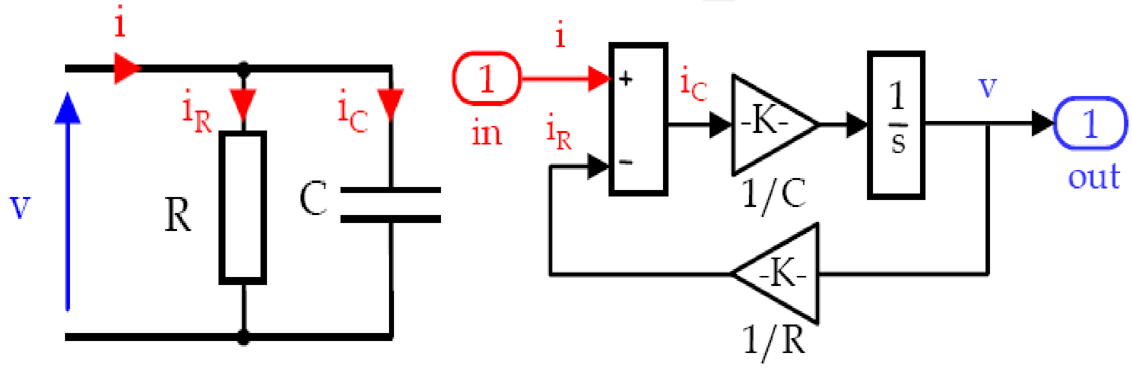

Figure 2.7: Model of a RC parallel dipole

2.9 DC-DC boost converter

Since the output power of the rectifier is DC, an average DC/DC boost converter is applied to regulate the DC link voltage. The average boost converter provides a reversed polarity output and enables the output voltage to be above or below the input voltage so it is suitable for WECS .MPPT controller generates duty cycle in order to create pulse width modulation (PWM) switching signals for the converter. The switching signal allows the boost converter to operate wind energy conversion system at optimum voltage and current so that the maximum power extraction is possible

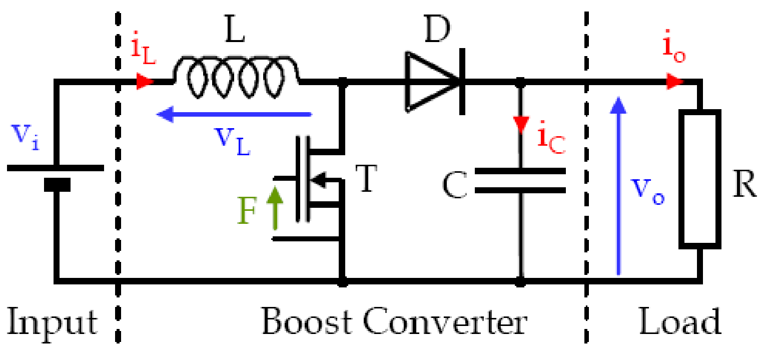

Figure 2.8:Boost converter circuit

Using equations when designing average boost converter

D1=(1-D)

VL=(Vg-(Vo*D1))/L (2.20)

IC=((I*D1)-Iload)/C (2.21)

I=$\int VL$ (2.22)

Iload= Vo/R (2.23)

Vo=$\int IC$ (2.24)

Where

D:duty cycle

Vg:input voltage

L,C are inductor and capacitor values

The rest of the simulation design of the average boost are in the appendix

2.10 MPPT Algorithms

In wind energy conversion system, the use of an MPPT controller is essential, since its important roleto extract the maximum energy produced by the PMSG generator whatever wind speed. its principleis based on the execution of MPPT algorithm which allows to reach and track the maximum power point(MPP). There are several MPPT techniques used in wind systems, this project will deal with fuzzy logic –based MPPT[9].

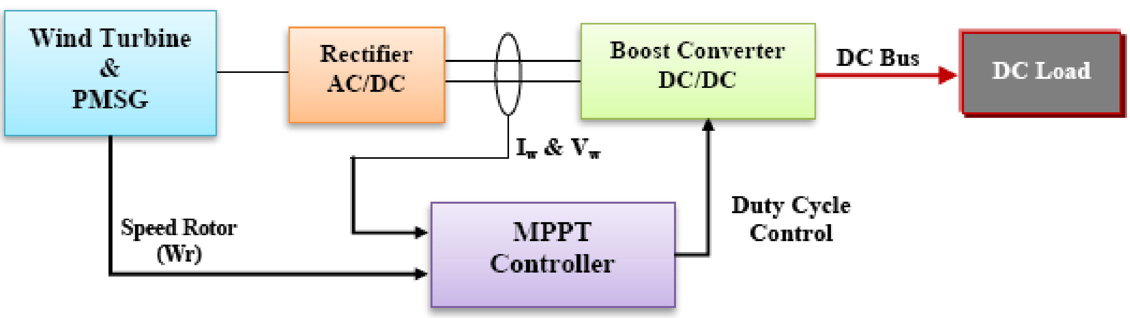

Figure 2.9: Wind energy system architecture.

2.10.1 Fuzzy Logic Technique

Fuzzy logic MPPT technique is considered as an extension for the HCS technique. It is governed by a set of rules which choose different control actions according to the state of the system at that instant while in HCS the control decision is taken based on only one if-elsestatement. The main advantage over Fuzzy logic based HCS is that it moves with a variable step size unlike HCS which uses a fixed step size. This help to minimize oscillations in the output. Like HCS, fuzzy control does not require to know system modeling [10], [11]. But it needs to define an optimal set of rules and corresponding control actions based on operation experience; calculating lots of boundaries and gains which differs from one system to another so the fuzzy controller has to be build dedicated to each system [12], [13]. The processing stage is based on a collection of logic rules in the form of IF-THEN statements. A block diagram for the proposed fuzzy controller is illustrated in Figure 2.10. The inputs for the proposed fuzzy are the error and the change of error as shown

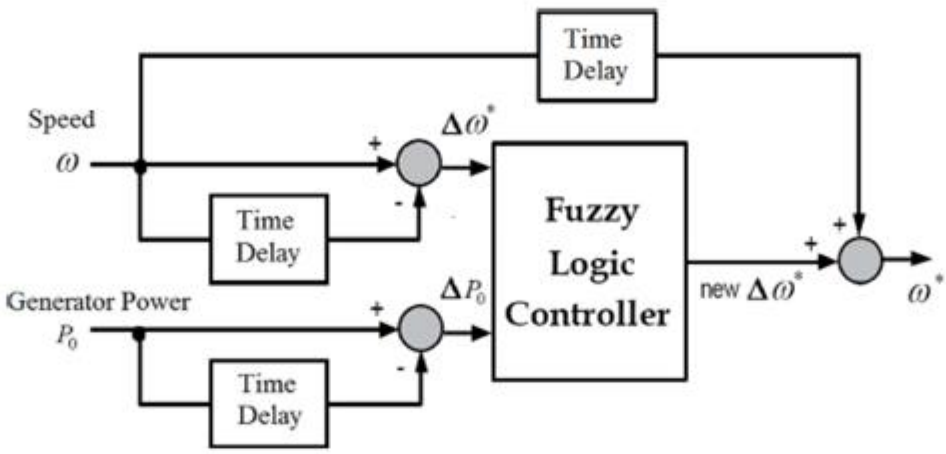

Figure 2.10: MPPT system with fuzzy based control.

For a particular wind speed, the rotational speed and output power should be measured by considering time interval 't' and then varying the rate of change value of 'D' (Δd) by using "fuzzy logic".

$\omega^* = \omega^* + \Delta\omega^*$

Fuzzy Logic rules control the generator restoring torque by considering dω/dt and dPe/dω as illustrated in Figure 2.11

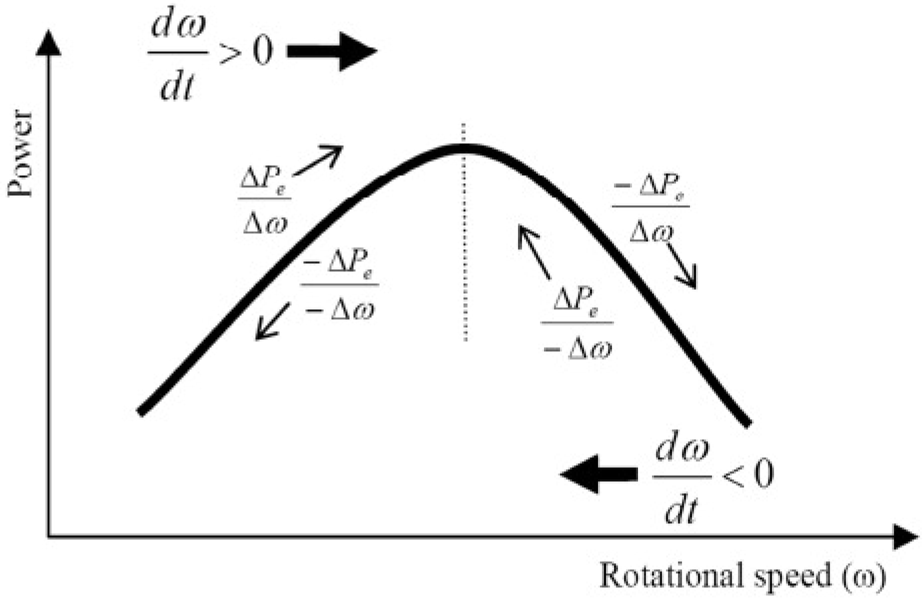

Figure 2.11: Fuzzy logic Control criteria

Advantages:

• Fuzzy control does not require any knowledge about system modelling or parameters.

Disadvantages:

• Fuzzy controller is not generic and it is built dedicated to each system depending on the operator experiences about that system.

The process of fuzzy logic is composed of four main parts as illustrated in Figure 2.12; fuzzification, fuzzy interface, rules base, and defuzzification.

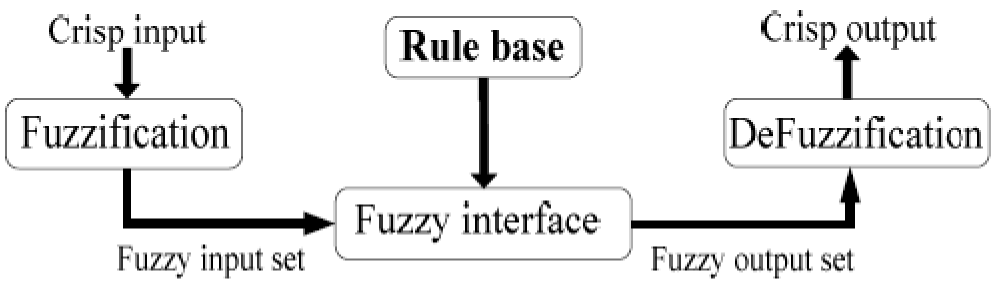

Figure 2.12: Fuzzy logic system.

First, a crisp set of input data are gathered and converted to a fuzzy set using fuzzy linguistic variables, fuzzy linguistic terms and membership functions. This step is known as fuzzification. Afterwards, an inference is made based on a set of rules where fuzzy decision is made based in the input fuzzy values. Lastly, the resulting fuzzy output is mapped to a crisp output using the membership functions, in the universe of discourse of the output variable. This last step is known as defuzzification step.

A fuzzy set μ(x)is a function from the input reference sets (Δw and Δp) to the unit interval.

The fuzzy sets will be μ(Δw) and μ(Δp). Five fuzzy sets (NL – NS – ZE – PS – PL) have selected for both two input variable (ΔwandΔp) while the left most and the right most functions have been selected to be rectangular. The remaining fuzzy sets are chosen to be triangular, as shown in fig. 2.13(a) . The above fuzzy values have the following meaning:

NL = negative large,

NS = negative small,

ZE = zero,

PS = positive small,

PL = positive large

The same configuration has been adopted for the output variable that is the duty cycle variation. It has to be mentioned that input variables and output one differ in their universe of discourse, where Δw is varying from -30 to 30 rad/s, Δp is varying from -5 to 5 MW and finally Δw* is varying from -1.5 to 1.5.

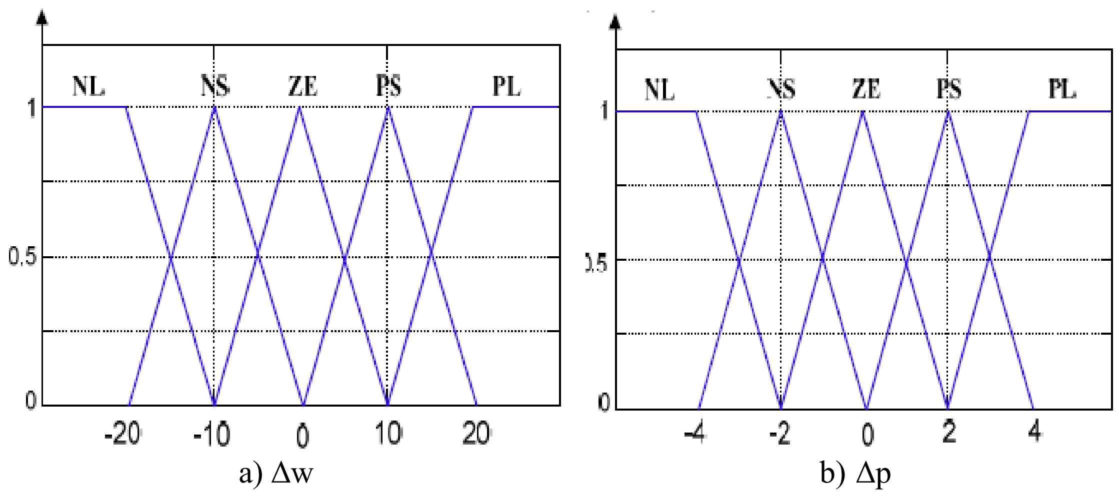

Figure 2.13(a): Membership functions of input variables

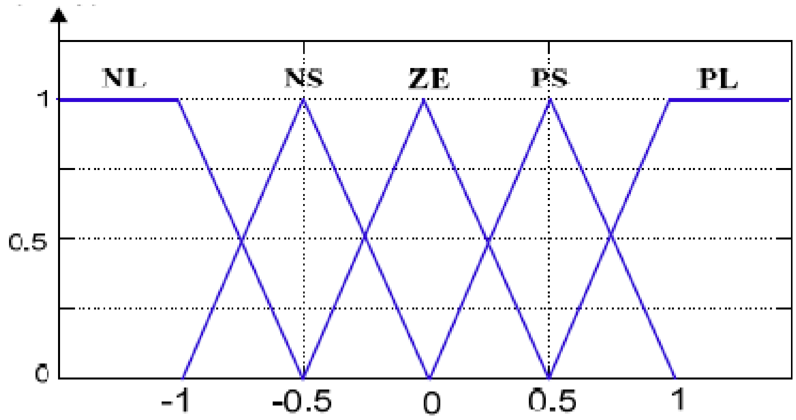

Figure 2.13(b): Membership function of output variable, Δw*

The fuzzy rule base is the important component in the fuzzy system. It is the control strategy relating input to output using their fuzzy values. As far as this fuzzy system is the MPPT controller, the fuzzy rules must be set to make the operating point climbing on the Power-speed characteristic of the wind turbine. This control strategy composed of IF-THEN conditional statements is given in table 4 [12].

.

Δw / Δp	NL	NS	ZE	PS	PL
NL	NL	NL	NS	NS	ZE
NS	NL	NS	NS	ZE	PL
ZE	NS	NS	ZE	PS	PS
PS	NS	ZE	PS	PS	PL
PL	ZE	PS	PS	PL	PL

Table 4: Fuzzy logic rules.

2.10.2 PI controller and its tuning method

The fuzzy system based MPPT provides the required rotor speed that corresponds to maximum power on the characteristic. A PI controller is used to accelarte the reponse of the system and ensure accurate MPP operation. The design of the controller parameters can be done using classical techniques if the transfer function is available. Another well-known technique that is based on experimental data of the system. It consists in exciting the system and performing some required tests to compute the parameters of the controller. This technique is known as Ziegler-Nichols method [14]. In fact, this method is based on experiments executed on an established control loop for the system model according to the following steps [15].

1. Set the true plant under proportional control, with a very small gain.
2. Increase the proportional gain until the loop starts oscillating.
3. Record the controller critical gain Kp = Kc (which is the gain which causes sustained oscillations in the signals in the control system without the control signal reaching the maximum or minimum limits) and the oscillation period of the controller output, Pu.
4. Then, the controller is tuned using Kc and Pu according to the formulas shown below in Table 5.

Controller Type	K_c	τ_i	τ_d
P controller	$0.5\ K_u$	-	-
PI controller	$0.45\ K_u$	$P_u / 1.2$	-
PID controller	$0.6\ K_u$	$P_u / 2$	$P_u / 8$

Table 5: Ziegler-Nichols' Ultimate Gain Tuning rules

CONCLUSION

This chapter is devoted to the modeling of wind driven permanent magnet synchronous generator. The principle of extraction of mechanical power from wind turbine is presented then the model of each component constituting the WECS has been modeled. For simplification, the synchronous generator has been modeled in the dq reference frame. From the wind turbine to the boost and gives the modeling of each component that will be used in the simulation frame work. This chapter presents also details about the MPPT algorithm that will be used to extract maximum power and that is based on fuzzy sets. The net chapter will investigate the simulation of the obtained model and the proposed MPPT algorithm.

3.1 Introduction

This chapter discusses the results of the simulation of WECS using fuzzy logic controller as MPPT controller. The performance of the proposed system is verified using MATLAB/SIMULINK model for 2.3 MW PMSG wind turbine as shown here(**3.1**).

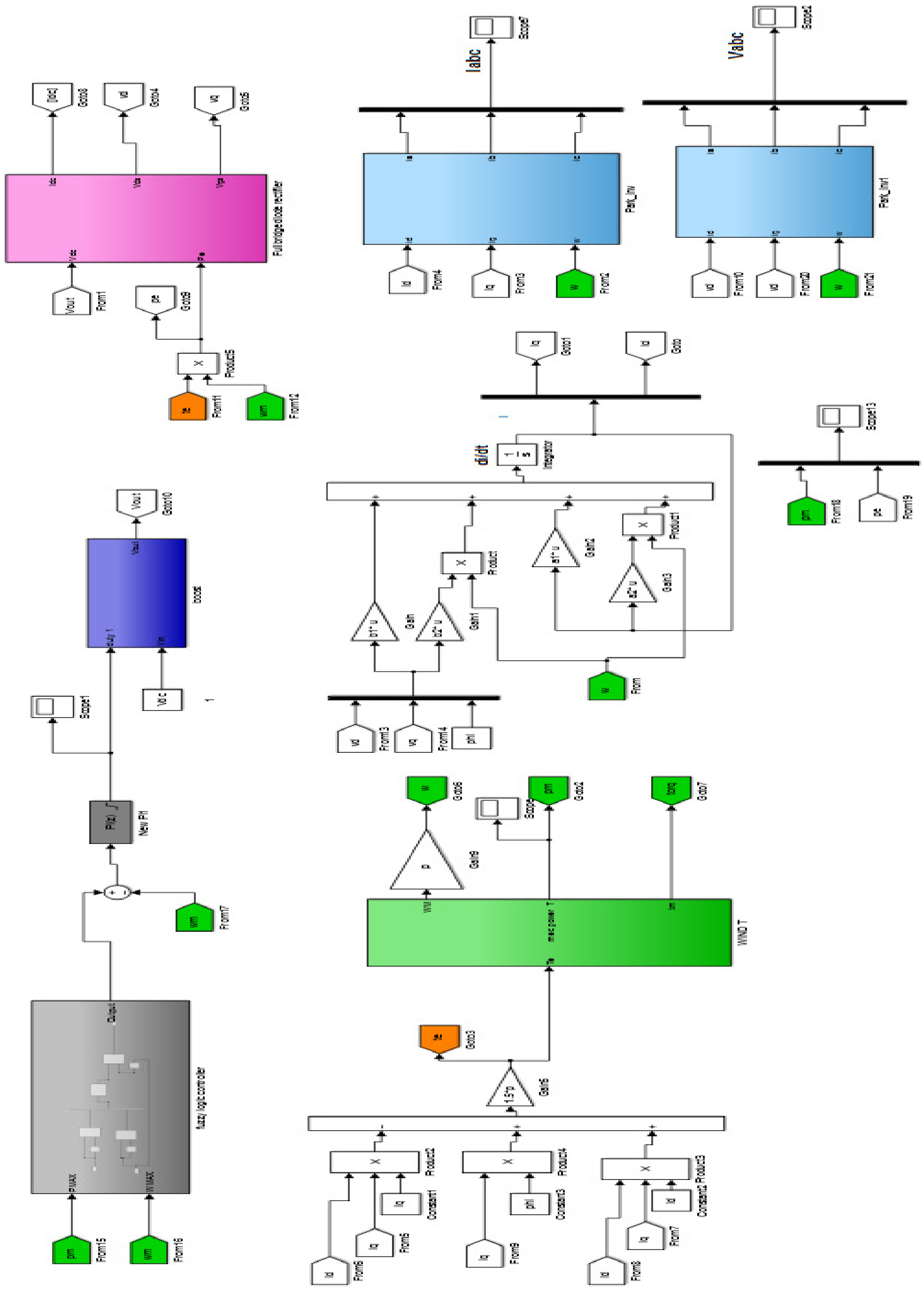

Figure 3.1:simulation scheme

The system performances are checked for three wind speeds following the profile shown in fig. 3.1.The first speed is 9m/s and lasts 2.4 sec. After that the speed goes up to 11m/s and then speeds up again to 12m/s for 4.5 sec .Figure 3.2 illustrates the relation between power coefficient and tip speed ratio (Cp - λ) showing optimal TSR for the designed turbine .

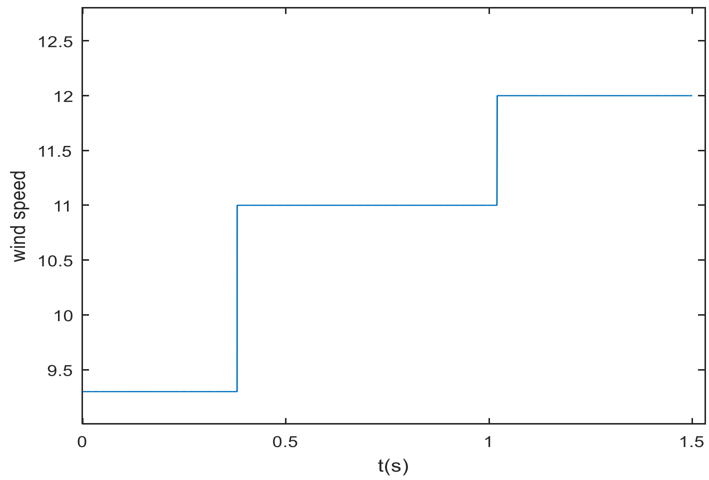

Figure 3.2: wind speed profile

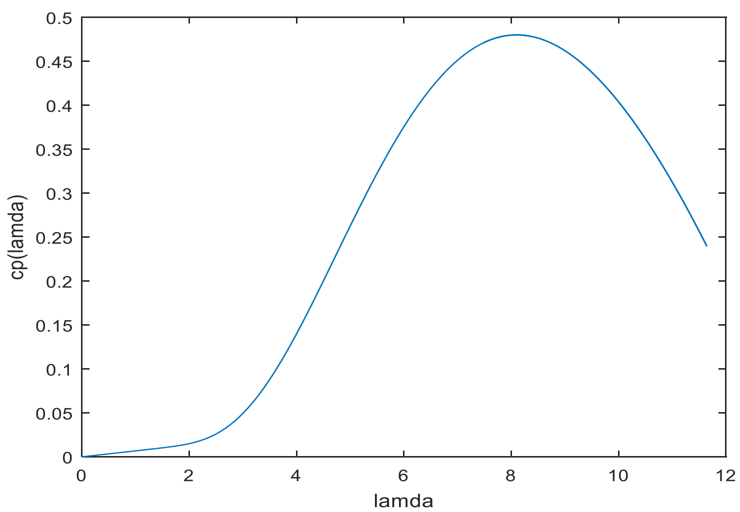

Figure 3.3: WT's Cp versus tip-speed ratio λ(TSR).

The designed wind turbine power characteristics curve is illustrated in Figure 3.3 showing the optimal power curves, while figure 3.4 shows Cp versus time.

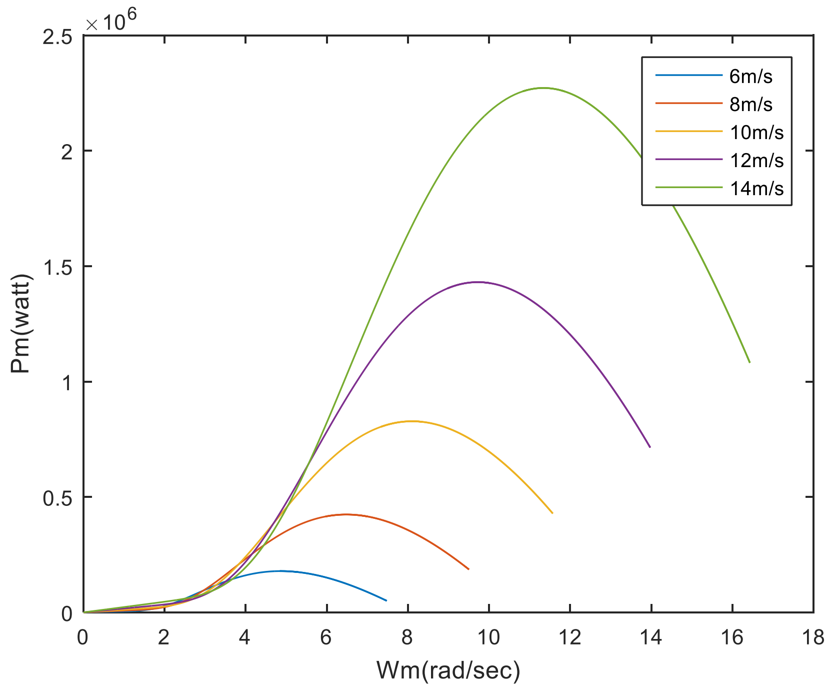

Figure 3.4: Wind turbine characteristics optimal power curve for different wind speeds

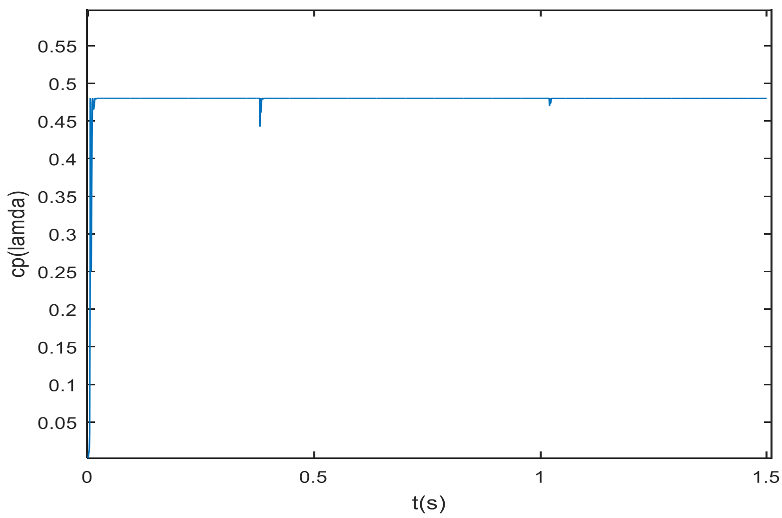

Figure 3.5: Obtained Cp versus time.

this figure shows that Cp has a fixed value (around 0.48) which is the max efficiency. This prove that the MPPT extract the max power from the wind .

3.2 Wind turbine outputs

We have computed the main parameters for the wind turbine: the mechanical torque ,mechanical power Pm and the radial velocity Wm where here the shaft between the wind turbine and the PMSG pass through gearbox with ratio of 3. Figure 3.5 shows the turbine output torque (Tm) at different wind speeds. Figure 3.6 will show the graph of the output mechanical power while figure 3.7 shows the wind turbine's rotational speed.

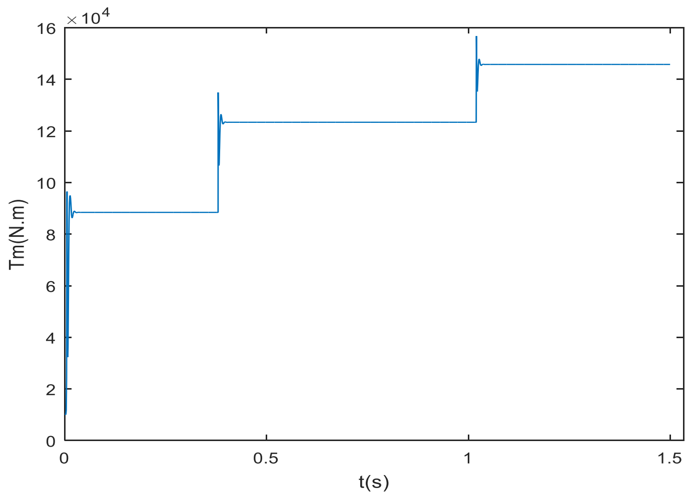

Figure 3.6: Wind turbine output torque, Tm .

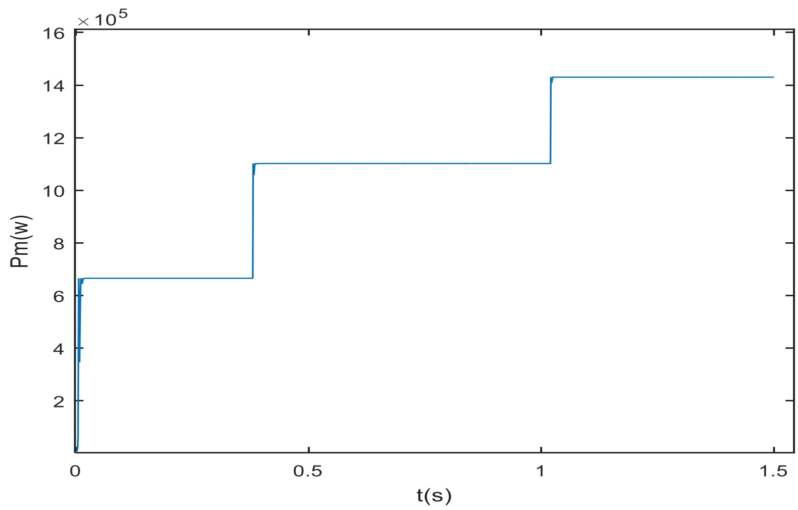

Figure 3.7: TheWT mechanical power Pm versus time

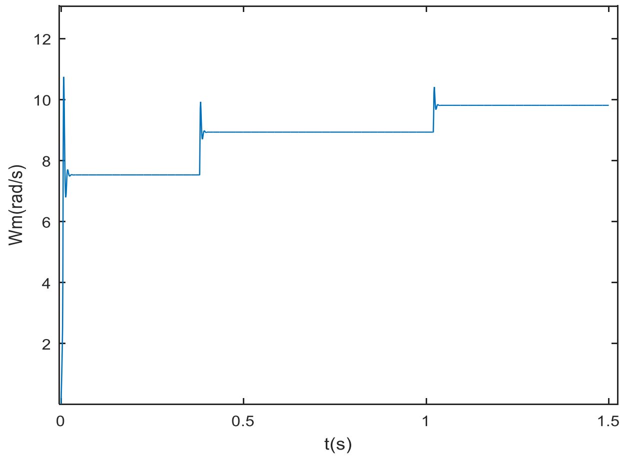

Figure 3.8: The rotational speed of the wind turbine

3.3 PMSG results

A perfect PMSG converts the mechanical energy into electrical energy without losses. However, due to the motion frictions, and losses in stator winding's copper, the output electric power must be lower than the extracted mechanical power. Due to the small values of losses compared to the rated turbine power, a zoom of fig.3.8 is performed. Figure 3.8(b). Figure 3.8(c) illustrate respectively the power losses in the WECS and the delay between Pe and Pm. This delay is the time needed for the system to respond and reach the appropriate rotor speed. Figure 3.9(a) and 3.9(b) will show the output voltage .we can notice that the voltage varies with the wind speed.

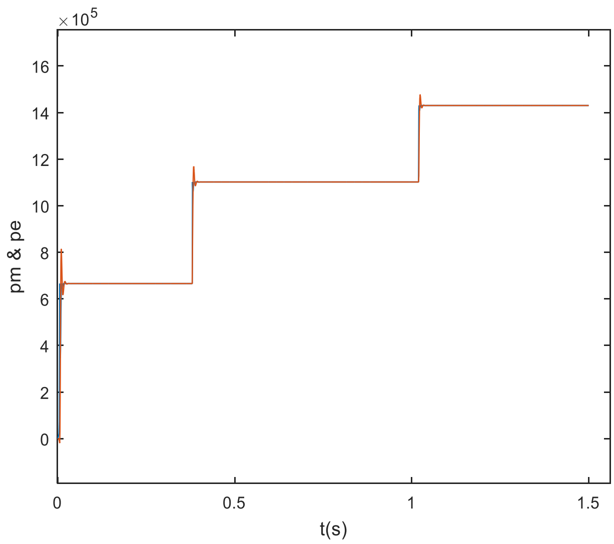

Figure 3.9(a): Simulation results: Pe & Pm

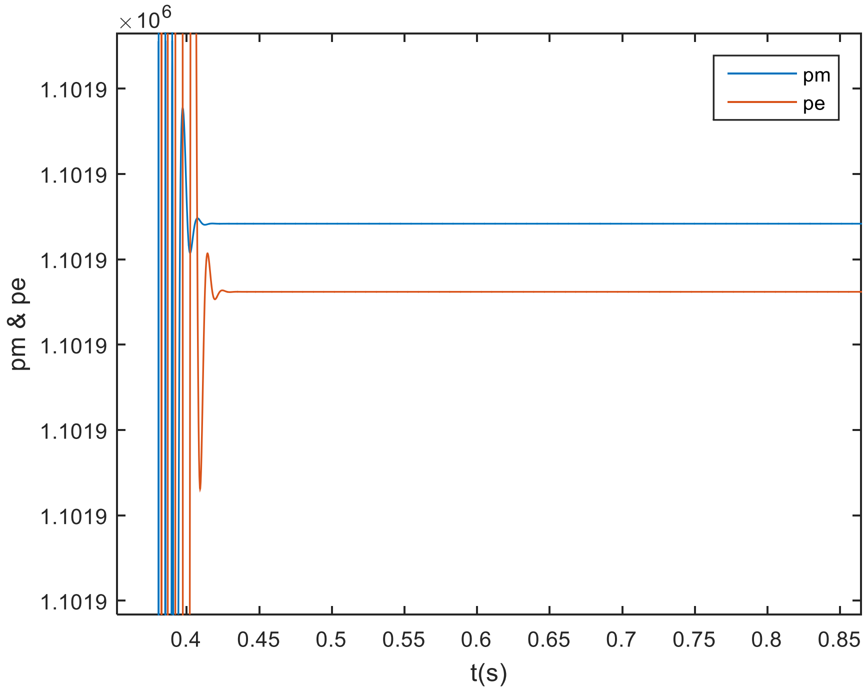

Figure 3.9(b): Zoom of fig.3.8 - Effect of losses in WECS

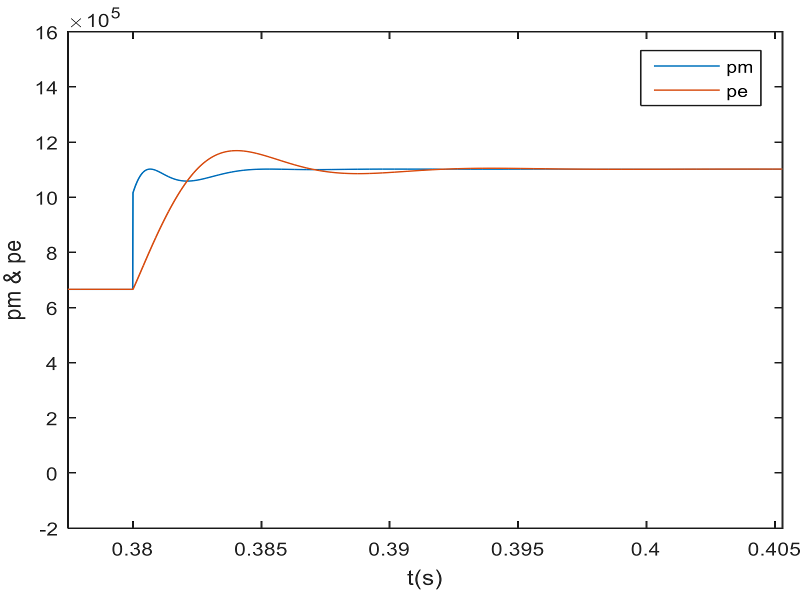

Figure 3.9(c): Zoom of fig. 3.8 – delay of Pe compared to Pm

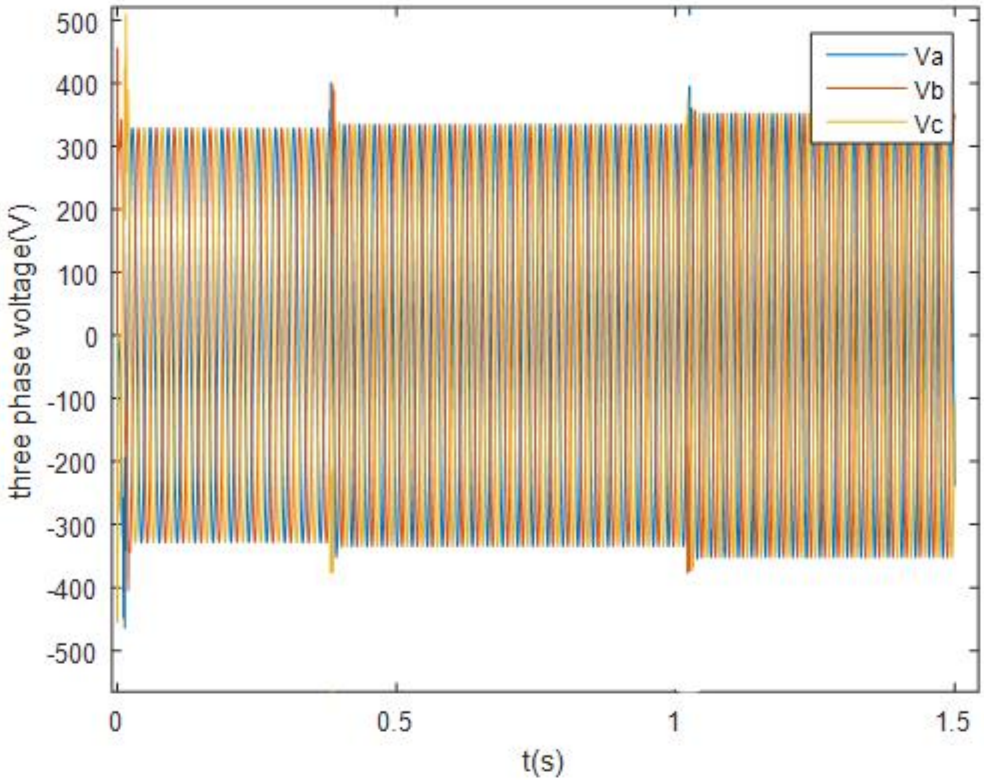

Figure 3.10(a): Output three phase voltage of the PMSG

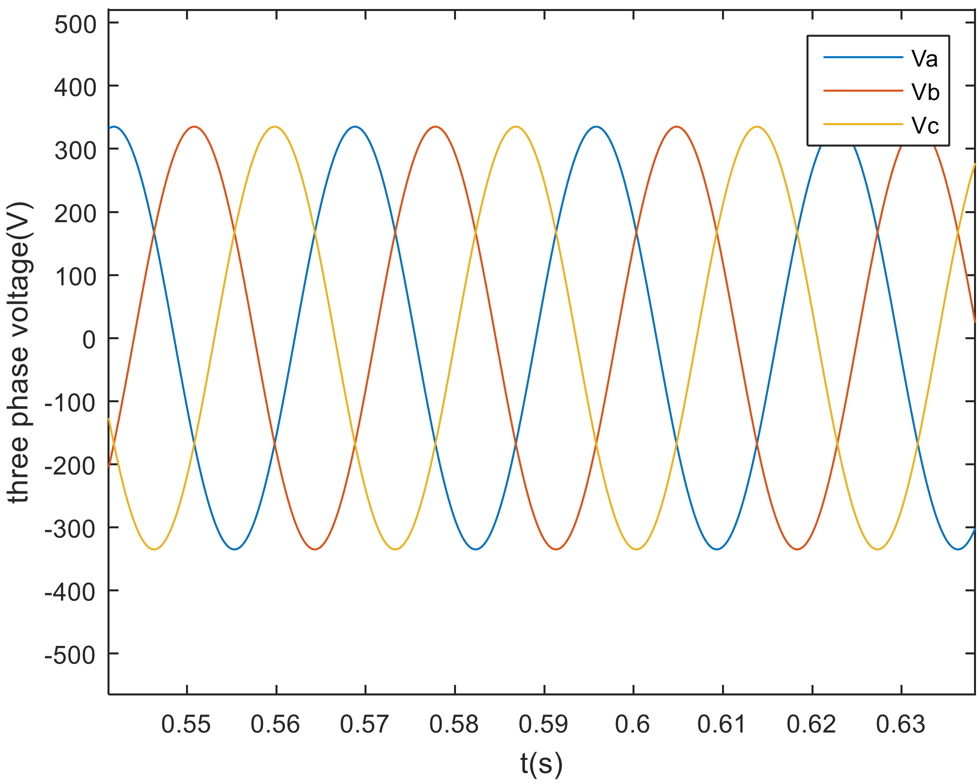

Figure 3.10(b): Simulation results : sinusoidal Vabc

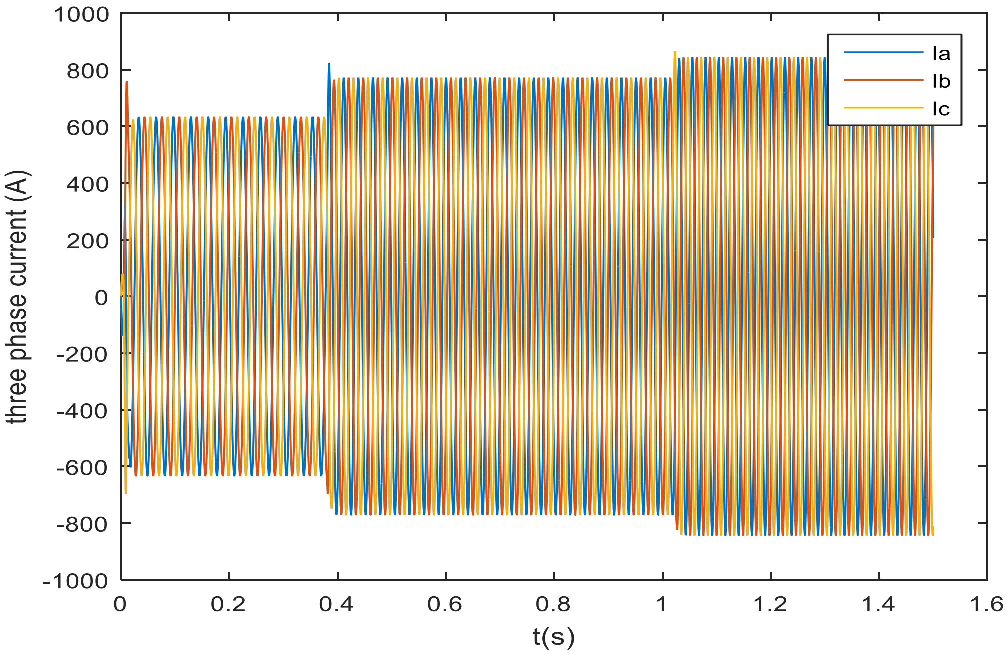

Figure 3.11(a): Output three phase current of the PMSG

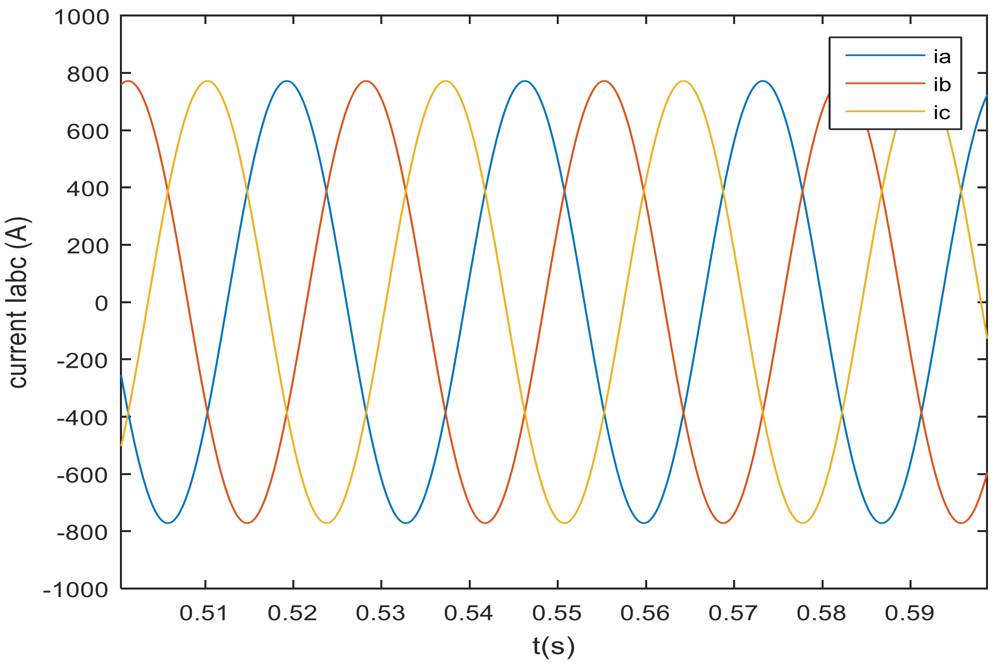

Figure 3.11(b): Simulation results : sinusoidal Iabc

3.4 Results of three-phase diode rectifier

The three-phase rectifier used in simulation is lossless bridge of 6 diodes to rectify the output of the generator. A filter is used to smooth out the voltage ripple. Result of simulation is shown in fig. 3.10. As the rotor speed increase, the output voltage of the rectifier increases too. Following the equation of the rectifier, the output voltage obtained at the output of the rectifier-filter system, the voltage tracks the path of the generator voltage.

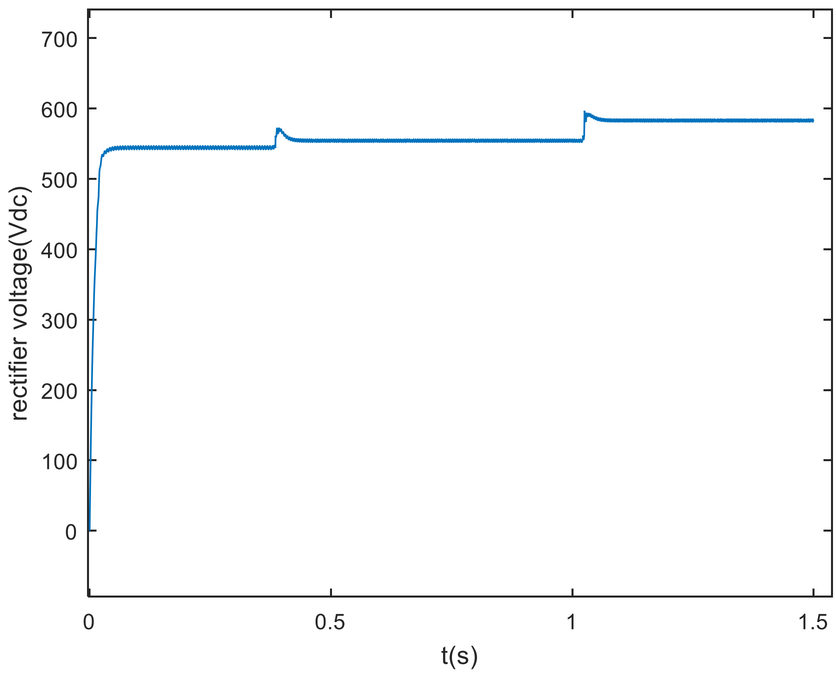

Figure 3.12: Output of rectifier –filter system

3.5 Results of the boost chopper

The FL-based MPPT controller sends a reference signal to the PI controller which forces the boost to give a fixed output voltage but the current varies to extract the MPP. This is achieved by varying the required duty cycle that makes rectified voltage following the generator voltage. At the same time the DC current is increased to allow this increase power to be extracted from the machine. This control strategy can be proved by comparing the output boost power with Pe.

The first figure illustrates the control signal of the boost. Figure 3.12 shows the Idc while figure 3.13(a) and (b) show respectively the output voltagein transient period and in steady-state.

One can observe some disturbances in figure 3.13(a) that occurred when the control signal changes due to the changing in power.

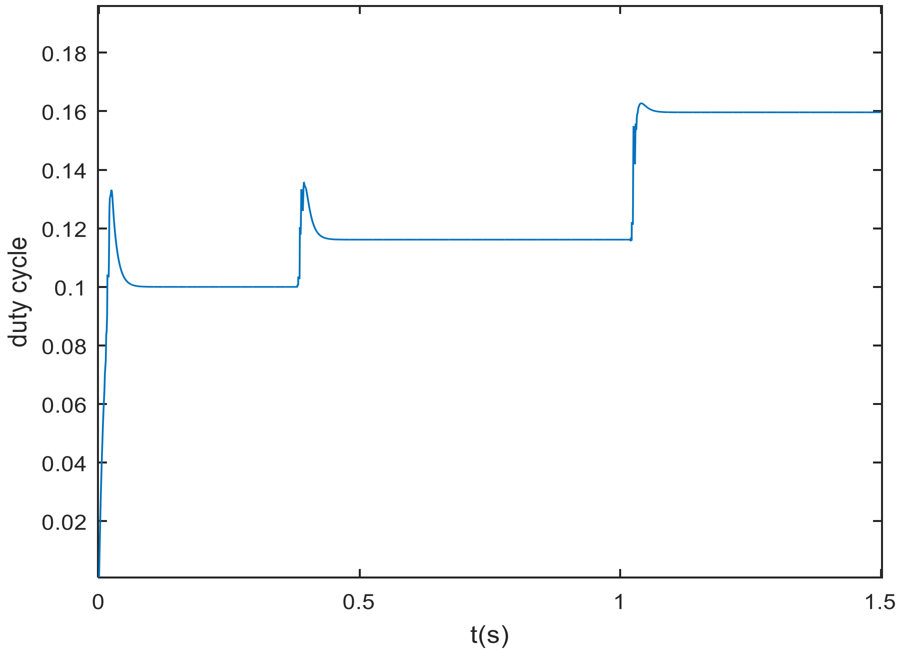

Figure 3.13: Control signal of the boost

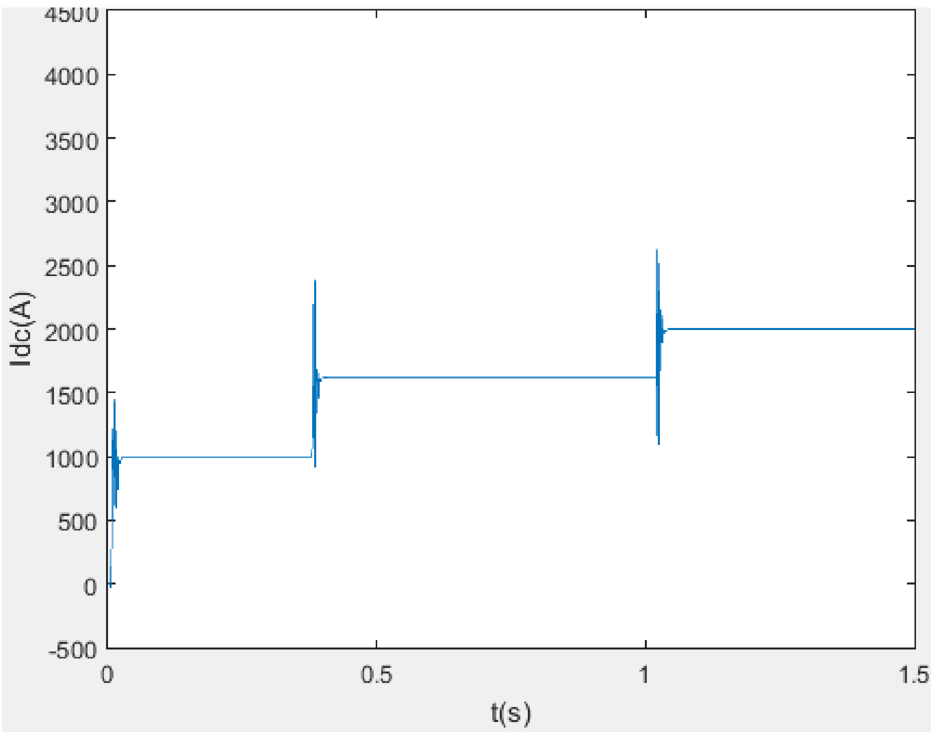

Figure 3.14: The DC current

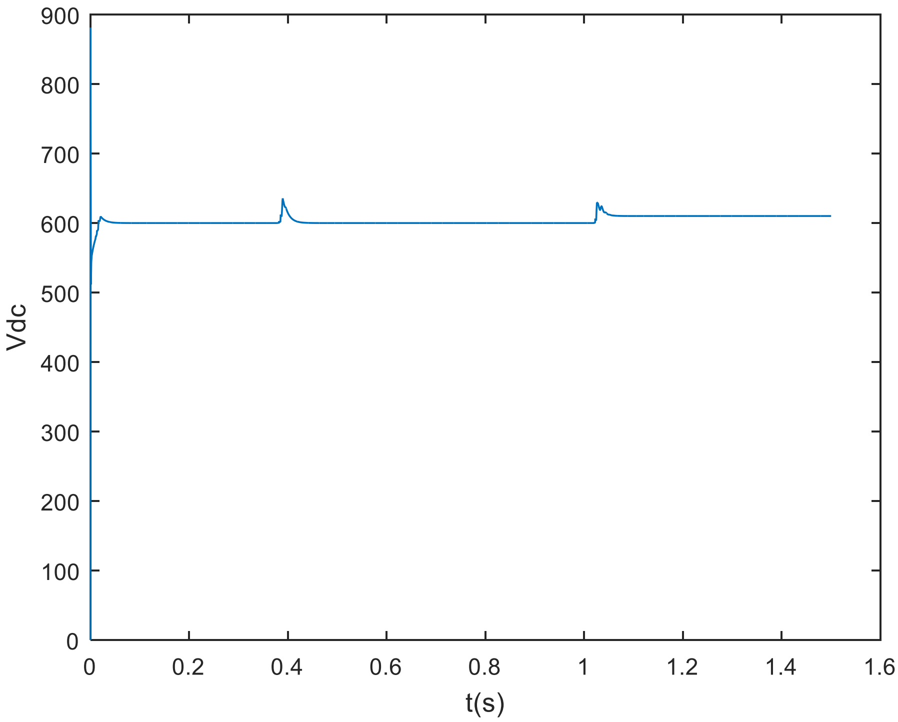

Figure 3.15(a): Boost output voltage _steady state

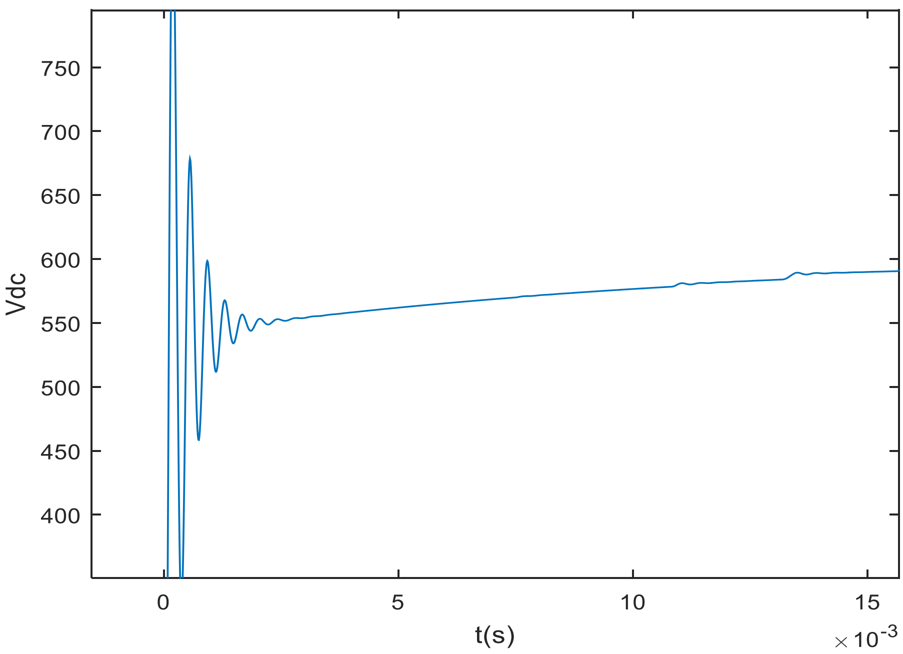

Figure 3.15(b): Boost output voltage - transient state

3.6 Conclusion

In this chapter, a simulation framework has been developed to check the effectiveness of the investigated fuzzy logic based MPPT algorithm. Results of each component composing the WECS, starting from wind turbine to the load, have been presented. The MPPT allows maintaining the output voltage constant and varying the DC current to extract the maximum power available in the generator. Comparison of the obtained power for the different wind speeds, shows that the investigated fuzzy MPPT is accurate in searching for the optimum speed. Therefore, its effectiveness in tracking maximum power is proven.

General Conclusion

With the evolution in the wind turbine aerodynamics and power electronic interface technologies, wind energy has become one of the most promising non-conventional renewable energy sources. Power electronic and intelligent control techniques make it available to control variable wind speeds and much more reliable to design large and small scale wind energy conversion systems (WECS).In this work, a fuzzy logic based MPPT controller has been presented for a 2MW variable speed wind turbine. Simulation using the mathematical model for the whole system shows its capability to track maximum power though the fluctuating wind speed.

This method offers several advantages:

- Independence of fuzzy MPPT controller w.r.t to the mathematical model of the system.
- Fuzzy controller is parameter free and any change in the system parameters, such as resistance, inductance.
- No need for wind speed or torque sensors,
- Accuracy of Maximum power tracking

However, the present work has been achieved for stand-alone application where the target can be water pumping, remote telecommunication system, remote village, etc. Therefore, still to be investigated, the effect of adding an inverter that will be synchronized with grid. The latter has some requirements to be satisfied according to the grid connection standards. Furthermore, the presence of rotor speed sensor that considered as the weakest element in the system can reduce the reliability of the system. To this, senseless control can be investigated to enhance the performance of the system.

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Appendix

Boost converter design

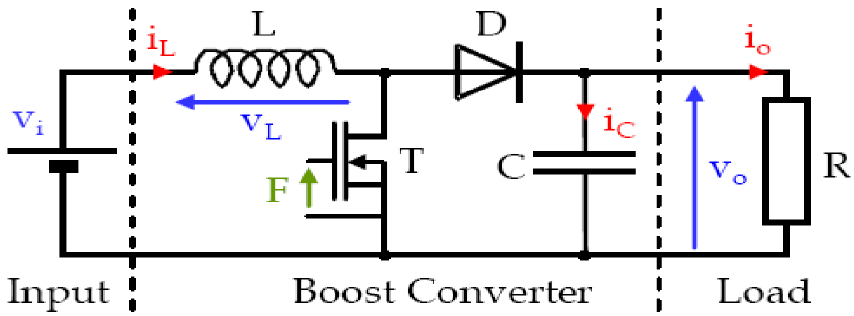

Figure:Boost converter circuit

designing boost converter as a matlab function needs to know the matlab function at continous mode, then finding all parameters that require.

<u>Matlab functions</u>

```
D1=(1-D);
VL=(Vg-(V*D1))/L;
IC=((I*D1)-Iload)/C;
```

```
Now,trying to find the values of D,L,C,R
Where:  D is duty cycle
        L is the inductor
        C is the capacitor
        R is the resistor
```

First of all , assume the value of the power, efficiency , the frequency and the values of both Vs and Vo wanted.

Let us take:

P=2*10^6 W , μ=100% , Fs=25000Hz

Then

<u>The duty cycle D:</u>

D=1 $-(Vs/Vo)$ *μ

<u>The inductor L:</u>

L=$\frac{Vs(min)*D}{Fs*\Delta Imin}$

Where

P=Is*Vs = 2*10^6 → find Is

P= Io*Vo=2*10^6 → find Io

$\Delta Imin$ = Imin *30%

<u>The capacitor C :</u>

C=$\frac{Io(max)*D}{Fs*\Delta Vcmax}$

Where Vc =Vo and $\Delta Vcmax$ =1% to 5% of Vmax

<u>The resistor R:</u>

Finally, P=$\frac{V2}{R}$ → R= $\frac{V2}{P}$