Addis Ababa University

Addis Ababa Institute of Technology

School of Electrical and Computer Engineering

Maximum Power Extraction of PMSG Based Variable Speed Wind Turbine Using Self-Tuning Fuzzy Controller

A Thesis Submitted to Addis Ababa Institute of Technology,
School of Graduate Studies, Addis Ababa University

in Partial Fulfillment of the Requirements for the Degree of Master of Science in Electrical Engineering (Control Engineering)

By

Addisie Belay

Advisor: Dr. Dereje Shiferaw

Addis Ababa, February 2017

Addis Ababa University

Addis Ababa Institute of Technology

Maximum Power Extraction of PMSG Based Variable Speed Wind Turbine Using Self-Tuning Fuzzy Controller

By

Addisie Belay

Approved by Board of Examiners

Chairman, Department of Graduate Committee	Signature
Advisor	Signature
Internal Examiner	Signature
External Examiner	Signature

Declaration

I, the undersigned declare that this thesis is my original work, and has not been presented for a degree in this or any other university, and all sources of materials used for the thesis have been fully acknowledged.

Addisie Belay Mengistu ____________________________

Name Signature

Place: Addis Ababa Institute of Technology, Addis Ababa University, Addis Ababa

Date of Submission: February, 2017

This thesis has been submitted with my approval as a university advisor

Dr. Dereje Shiferaw ____________________________

Advisor's Name Signature

ACKNOWLEDGMENT

First of all, I would like to thank my advisor Dr. Dereje Shiferaw, for his bright guidance, expert advice and showing me the right way of carrying out the thesis.

Moreover, I wish to express special gratitude to my family members for their encouragement, support and belief in me all these years. More than all, I would like to thank my mother, Muchite Tadesse, for her back-up towards my education, I feel it would be incomplete without the help of her; I love you so much my mom. Also, I would like to thank my husband, Badma Taye, for his understanding, support, patience, belief in me and true love.

Finally I extend my gratefulness to all of my classmates and friends for their directly and indirectly help and support during the thesis work.

Table of Contents

LIST OF FIGURE

LIST OF TABLE

LIST OF ACRONYMS

AC ....Alternating Current

DC ....Direct Current

DFIG ....Doubly-Fed Induction Generator

PMSG.....................................Permanent Magnet Induction Generator

PWM ....Pulse Width Modulation

PE...Power Electronics

DQ..Direct Quadrature

EMF..Electromotive Force

IGBT ....Insulated Gate Bipolar Transistor

MOSFET.................................Metal-Oxide-Semiconductor Field-Effect Transistor

CCM.......................................Continuous Conduction Mode

MPPT ....Maximum Power Point Tracking

HAWT ....Horizontal Axis Wind Turbine

VAWT ....Vertical Axis Wind Turbine

PID ....Proportional Integral Derivative

FLC ....Fuzzy Logic Control

GTP...Growth and Transformation Plan

WEC ....Wind Energy Conversion System

MCU ....Micro-Controller Unit

DSP...Digital Signal Processor

PFC ....Power Factor Correction

SCIG..Squirrel Cage Induction Generator

WRSG.....................................Wound Rotor Synchronous Generator

ABSTRACT

The interest in wind energy system is growing worldwide to reduce dependency on fossil fuel and to minimize the adverse impact of climate change. However, because of its unpredictable and random availability, wind power management concepts are essential to extract as much power as possible from the wind when it becomes available.

The purpose of this thesis is to develop fuzzy logic controller to tune the parameters of PI controller for a maximum power tracking strategy of variable speed wind turbine. The system consists of 8.5kW direct drive permanent magnet synchronous generator (PMSG), uncontrolled rectifier which is used to convert the ac output voltage from the wind generation unit into dc voltage, a dc/dc switch-mode step up boost converter which is used to catch the maximum power from the wind, and a power control system. The output of the controller was given to the dc-dc converter to adjust the duty cycle and when adjusting the duty cycle the rotor speed of PMSG was controlled to get the maximum power. The proposed control algorithm allows the generator to track the optimal operation points of the wind turbine system under fluctuating wind conditions. This algorithm does not require the knowledge of intangible turbine mechanical characteristics such as its power coefficient curve, power characteristic or torque characteristic instead it uses rotor speed measurement as control variable inputs. MATLAB simulation study results confirm that the proposed controller algorithm is effective in tracking maximum power with good dynamic and steady state performance.

From the power extracted plots it is observed that the overshoot given by the self tuning fuzzy PI controller is reduced to 0.09% from 0.2% while the regulation time is reduced to 0.6 s from 1.4s from the PI controller, when the wind speed is 12 m/s (steady state). The overshoot given by the self tuning Fuzzy PI controller is reduced to 0.07% from 0.1% and 0.01% from 0.09% in comparison with the PI controller while the regulation time is reduced to 5.4s from 6.1s and 10.5s from 11.2s from the PI controller, when the wind speed changes suddenly from 12 m/s to 10 m/s and 10m/s to 8m/s respectively.

Keywords- Variable Speed Wind Turbine, Permanent Magnet Synchronous Generator, Uncontrolled Rectifier, DC/DC Switch-Mode Boost Converter, PI Controller, and FLC.

CHAPTER ONE

INTRODUCTION

1.1 Background of the Study

Energy is one of unfulfilled human need, in which human beings are exploring many things in order to satisfy this desire. Even though there are different sources of energy, wind energy is technically the second most important resource next to hydropower for power generation.[1] Wind power is renewable clean energy with short construction periods. As a renewable technology, wind energy also offers important environmental benefits including: no emissions of carbon dioxide, sulfur and nitrogen oxides, or other air pollutants and any wastes or residues.

In recent years, the environmental pollution has become a major concern in people daily life and a possible energy crisis has led people to develop new technologies for generating clean and renewable energy. Wind power along with solar energy, hydropower and tidal energy are possible solutions for an environmentally-friendly energy production. Recent trend indicates that wind energy will play a major role to meet the future energy target worldwide to reduce reliance on fossil fuel and to minimize the adverse impact of climate change. Over the last decade, the global wind energy capacity has increased rapidly and wind is an important competitor to the traditional sources of energy. Due to the environmental and economical reasons the penetrations of wind energy in power systems is rapidly increasing worldwide. It is predicted that by 2020 up to 12% of the worlds electricity will be supplied from wind power. [1] [2]

Ethiopia is also aims to become the region’s leading producer of renewable energy and plans 800MW of wind power by constructing and implementing wind farms that will be directly integrated with the country’s grid system with in the coming three to five years as set by national growth and transformation plan (GTP). The first wind installation in the country was the 51MW Adama I wind farm built in 2011. The 120MW Ashegoda wind farm opened in October 2013 and was the largest wind farm in Africa at that time. The largest 153 MW Adama II wind farm opened in May 2015, bringing Ethiopia’s installed wind capacity to 324MW total. For the future time, Ethiopia is aiming at a power system generation capacity expansion towards renewable energy. This renewable energy will increase the access of electrical energy demand.

1.1.1 Components of a Wind Turbine Generator System

The major components of a wind turbine-generator system are shown in Figure.1.1. It consists of blades, rotor hub and other components such as turbine shaft, gearbox, generator shaft, etc. the whole system is designed in such a way that it transfers the mechanical energy into the electrical form. The wind blown into the turbine is causing it to spin and hence it generates electricity. The yaw control system is used in order to align the direction of the rotor faces into the wind. [3]

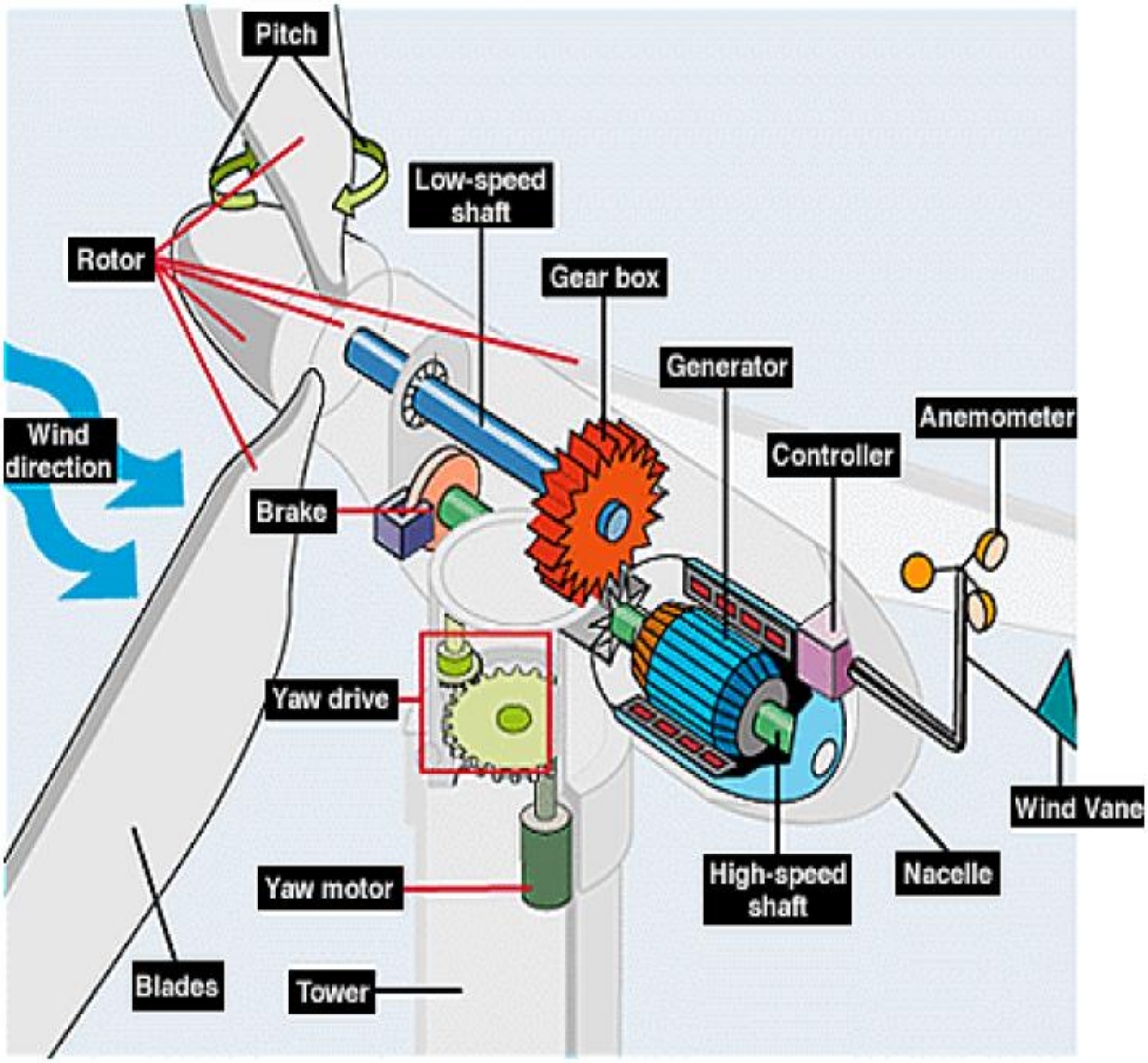

Figure 1.1Components of Wind Turbine System (Mechanical, Electrical Components) [3]

The blades and the hub together are called the rotor. It is the rotating component which converts kinetic energy available in the wind to mechanical energy. The rotor hub connects the rotor blades to the rotor shaft. It is also the place where the power of the turbine is controlled physically by pitching (A method of controlling the speed of a wind turbine by varying the orientation) the blades. Blade is a rotating component designed aerodynamically to work on the principle of lift and drag to convert kinetic energy of wind into mechanical energy which is transferred through shaft then converted to electrical energy using generator. Most turbines have either two or three blades. [4].

The nacelle is an enclosure that sits top of the tower and contains the gear box, low speed shaft and high-speed shaft, generator, controller, and brake. The nacelle also protects turbine components from atmospheric weather conditions and reduces noise. Low-speed shaft is the principle-rotating element which transfers torque from the rotor to the rest of drive train. It also supports the weight of the rotor. It is connected to the gearbox to increase the rpm. On the other hand, high speed shaft transmits the speed & torque from the gearbox and drives the generator. Gear box is also one of the costliest (and heavy) parts of the wind turbine that steps up the speed according to the requirement of the electric generator.

The generator converts wind’s mechanical power to electrical form. The voltage at generator’s terminal is low so a transformer is used in order to step up the voltage to the grid voltage level. The transformer could be placed in the nacelle for minimization of losses or at the bottom of the tower [6]. Other parts of wind turbine are anemometer and wind vane which are used for measuring the wind speed and wind direction respectively. We need to measure the wind speed to decide whether we should start up the wind turbine or in case the wind speed is too much, we should shut the turbine down due to safety issues. During the periods of extremely high winds and maintenance, brakes are used to stop the wind turbine for its safety. The wind direction is used for the yaw control system in order to align the nacelle into the wind’s direction. The controller starts up the machine at cut-in wind speed (generally 4 m/s) and shuts off the machine at cut-out wind speed (generally 25 m/s) as per the design requirement [7].

1.1.2 Wind Energy Conversion Systems (WECS) Configurations

Generally speaking, wind power generation uses either fixed speed or variable speed turbines. The main differences between these wind turbine types are the ways how the aerodynamic efficiency of the rotor would be limited for different wind speed conditions.

i. Fixed Speed Wind Turbine WECS

Fixed-speed WECS operate at constant speed. That means that, regardless of the wind speed, the wind turbine rotor speed is fixed and determined by the grid frequency. Fixed-speed WECS are typically equipped with squirrel-cage induction generators (SCIG). The fixed speed WECS starts to produce power when the wind speed is higher than the cut-in speed (3-4 m/s). At a speed higher than the rated wind speed (13 to 15 m/s), the power captured by the turbine is limited either by active/passive stall or pitch control of the rotor blades. At a speed higher than the cut-out speed (around 25 m/s), the turbine is stopped by either full stall or full pitch of the blades to protect the turbine and generator from possible damage [8]. The rotating speed of large fixed speed turbines is normally in the range of 6 to 15 rpm, whereas the induction generator operates at much higher rpm (750 rpm to 1800 rpm). The generator operating speed is determined by the number of poles and grid frequency [8].

The advantages of fixed-speed wind turbines are as follows [9]:

- Simple electrical system;
- High reliability;
- Moderate cost.

Their major disadvantages are as follows: [9]

- The extracted power is not optimized: With this type of wind turbine, we have not the possibility of adjusting the power generated.
- Lack of reactive power management by induction generator. The direct connection of an induction generator to the grid requires the addition of capacitor banks to reduce reactive power required to the grid.

ii. Variable-Speed WECS

Variable-Speed wind turbines are currently the most used WECS. The variable speed operation is possible due to the power electronic converters interface, allowing a full (or partial) decoupling from the grid. For this, a variable-speed operation will be necessary to maximize the power extracted from the wind. But in this case, a direct connection to the grid is not possible because of the stator voltage frequency variations. A power electronic (PE) interface between the generator and the grid is necessary. It consists of two converters (a rectifier and an inverter) connected via a DC voltage bus.

The advantages of variable-speed wind turbines are as follows [9]:

- It can supply power at a constant frequency and voltage although the rotor speed could vary
- Active and reactive power could be controlled independently
- It can follow a Maximum Power Point Tracking (MPPT) strategy when the wind speed is less than rated, so the maximum energy of the wind will be absorbed by this type of turbine.

However there are some disadvantages for this type of turbine such as:

- Generation of variable frequencies and as a result it needs complex power electronics converters.

Table 1.1 Comparisons Between Fixed Speed and Variable Speed Wind Turbines.

WECs wind turbine types	Fixed Speed	Variable speed
Advantages	• Low cost • Low maintenance • Simple and Robust construction	• Independent control of active and reactive power • Higher efficiency
Disadvantages	• No control over the active or reactive power • Less efficiency • Less power factor • Higher stress on turbine	• Higher cost of power electronics • Limited fault management Capability

1.1.3 Operating Regions of a Wind Turbine Generator System

The wind turbine always operates with different dynamics, from minimum wind speed to maximum wind speed, and the operating regions of the wind turbine can be illustrated by their power curve shown as in Figure 1.2. Three wind speeds and two operation modes are shown in this power curve, and their definitions are as given below [9] [10]:

a. Cut-in Speed: The cut-in speed is the minimum wind speed at which the wind turbine will generate usable power. This wind speed is typically between 3.5 and 4.47 m/sec for most turbines.
b. Rated Speed: The rated speed is the optimum wind speed at which the wind turbine will generate its designated rated power. At wind speeds between the cut-in speed and the rated speed, the wind turbine will operate at the "maximum power point tracking (MPPT) mode", and the output power of a wind turbine will increase as the wind speed increases.
c. Cut-Out Speed: At very high wind speeds, typically between 22 and 45 m/sec, most wind turbines cease power generation and are shut down for protection purposes. The wind speed at which shut down operation occurs is called the cut-out speed. When the wind turbine experiences high wind speed, the mechanical part of the wind turbine may be damaged, and hence having a cut-out speed is a safety consideration.

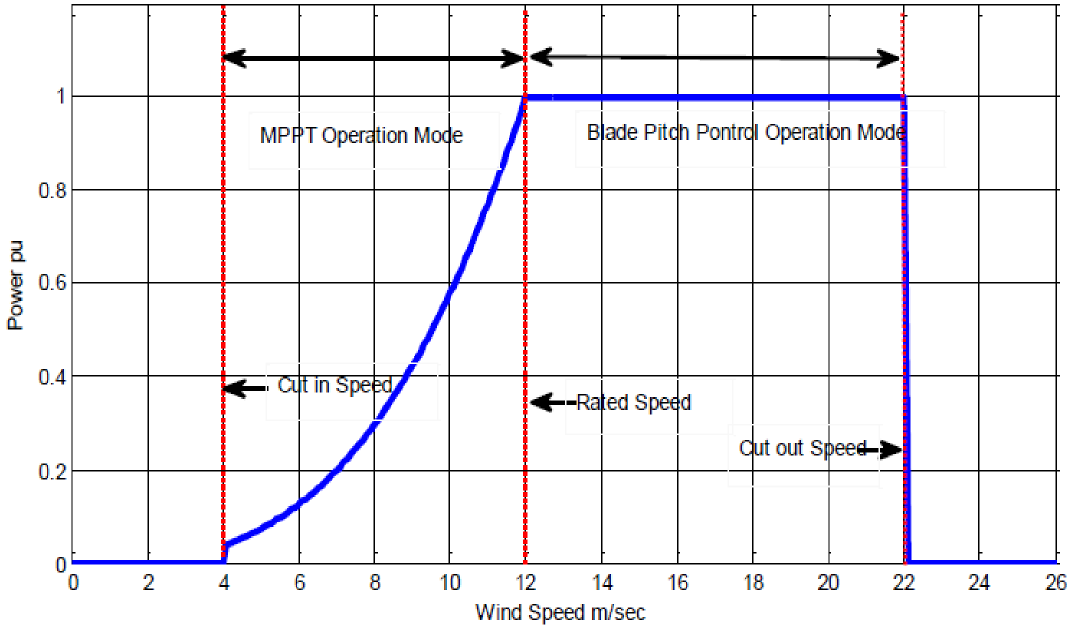

Figure 1.2 Power versus Wind Speed Curve [10]

When wind speed is below rated wind speed value, the power extracted from the wind must be maximized until the wind speed reaches its rated value, which is known as maximum power point tracking (MPPT).

1.1.4 Wind Turbine Power Control

There are several ways to control the power output of wind turbines. These methods depend on the design of the wind turbine and its parameters, for example a fixed-speed wind turbine will have a different power control system than a variable speed wind turbine. The mostly used control strategy is in terms of generator speed, and torque control, pitch angle control, maximum power point tracking (MPPT), and so on.

a. Aerodynamic Torque Control

The purpose of this method is to change the rotor geometry in order to make the turbine more or less efficient, therefore affecting the aerodynamic torque in the shaft. The rotor geometry can be change by changing the blade pitch angle or by changing the geometry of a section of the blade. As of today, blade pitching control is the most effective way to influence the aerodynamic angle of attack and therefore the input power [15]. In order to affect rotor geometry without a blade pitch controller, one needs ailerons. These are independent wings that will move with the change in wind and change the geometry of the blade. But this control method requires the knowledge of the wind speed to determine the pitch angle that will extract the maximum available power from the wind, thus making this method as accurate as the accuracy of the wind speed measurements.

b. Generator Torque Control

The power output of the wind turbine can be controlled by changing the generator torque. The control methods used depends on the type of generator and the connection to the grid. Grid-connected generators need to operate with a very small speed range in order to maintain the speed at or near synchronous speed. For this reason, the generator torque needs to change quickly to compensate for the rotor torque and keep the speed nearly constant.

One way to control the generator torque is by using power electronic converters. Using power electronics allows for a rapid change in the generator torque without necessarily affecting the power output to the grid. In addition, the generator can be controlled rapidly and can adapt faster to the changes in the wind. It is the converter’s task to control the torque of the generator, so that the mechanical power output from wind turbine is being controlled. At partial load, this method of control can be used to maximize the power output of the turbine.

c. Yaw Orientation Control

The method of yaw orientation power control is very simple to understand. In order to reduce the power output of the turbine, the rotor is rotated or yawed out of the wind. There have been a number of different designs developed for this type of control, but typically they are used in small wind turbines [16].

1.2 Problem Description

Generation of wind power involves extraction of energy from the wind by use of the wind turbine generator. But turbines do not naturally operate at the optimum rotor speed for any given wind velocity because its rotor speed is dependent on the generator loading as well as the wind speed fluctuations and a small variation from the optimum rotor speed will cause a significant decrease in the power extracted from the wind. [14] Therefore to achieve and extract maximum power from the wind available for any given wind speed, it is necessary to control the nonlinear and time variant wind energy conversion system through its power interface. For this purpose, linear and nonlinear control techniques were proposed in the literature. Linear controllers are depending on the knowledge of wind speed, turbine parameters and the precise mathematical model but as the turbine ages, its parameters change, means that the controller needs to be re-tuned to compensate for these changes. As a result they cannot always effectively control systems with changing parameters or strong nonlinearities.

To overcome this problem, this thesis work proposes a highly reliable and fast acting controller which is self-tuning fuzzy logic controller and applied for controlling the duty cycle of the switch-mode DC-DC boost converter so that it tracks its optimal values in order to extract the maximum possible power from the wind.

1.3 Objectives

1.3.1 General Objectives

The main objective of the thesis is to extract maximum power from the wind available, especially at partial load (when the wind speed is less than the rated wind speed) for the generation system by using self-tuning fuzzy logic controller principle.

1.3.2 Specific Objectives

The specific goals of this thesis are:

- To study the feasibility of using fuzzy logic control algorism in WECs System
- To select appropriate power converter and wind turbine type with respect to the type of electric generator used
- To study and develop the mathematical models of wind energy conversion system
- To simulate the system model using MATLAB/Simulink environment

1.4 Relevance of the Study

Wind energy is an important source of electrical energy in years to come. Its main advantages come from the fact of being a renewable and environmental friendly energy [17]. For example, as we know in Ethiopia, the most dominant energy source is hydropower energy but at the dry season the annual rain fall is decrease as a result the hydropower dams cannot maintain full reservoir water to generate power during the full load hours that leads to severe power shortage. As the wind potential is very high during the dry season where hydro dams suffer for lack of water, Wind power can balance the increasing energy demand versus energy production. The other advantage of wind power is that it has short construction periods. Since wind energy is unpredictable in nature it needs the control technique for the aerodynamic power extracted from the generators.

To do this, Fuzzy logic controller is advantageous than conventional controllers because:

- The controller relies on the actual performance of the wind turbine rather than on theoretical data on turbine characteristics
- The control algorithm is universal and may be adapted to various systems with minimal adjustments and relatively unaffected by variations in turbine inertia and wind speed.

1.5 Methodology

The research methodology of the thesis involves a number of different tasks that are performed to lead towards completion. The first task is to describe the statement of the problem and define the objectives of the research. This is followed by the literature review where all the theoretical information regarding the maximum power extraction of PMSG based wind energy system is gathered, a comparison of previous similar research is also presented.

After gathering information, the detail mathematical model of wind energy conversion system including Wind Turbine (Aerodynamic) and drive train model, generator model and boost converter model are discussed. A brief description on the fuzzy logic theory and control algorithm is then presented. In the fuzzy logic controller design, the first step is identifying and gathering the crisp set of input data and converted to a fuzzy set using fuzzy linguistic variables, fuzzy linguistic terms and membership functions. This fuzzy linguistic term is then converted to fuzzy IF THEN rules and crisp outputs using intuition method. The rule tables are constructed with the development of membership functions for fuzzy logic controller.

The controller is designed using PI tuned with fuzzy logic. Simulation studies are carried out for different wind speeds to show the advantages of the proposed self tuning fuzzy controller compared to the conventional maximum power extraction controller. The final stage is the conclusion based on the research findings.

1.6 Outline of the Thesis

Including this introductory chapter, this thesis is organized in six chapters. Chapter one presents the introduction, statement of the problem, objectives of the study, contribution of the study and the methodology leading towards the completion of the thesis.

The second chapter discusses in brief about the general literature review of wind energy conversion system and its controlling technique.

Chapter three describes how wind turbines extract energy from wind. This chapter gives the detailed mathematical model of wind energy conversion system including Wind Turbine (Aerodynamic) and drive train modeling, generator model and boost converter model are discussed.

Chapter four presents the fuzzy logic controller design. The selection of membership functions and the construction of rule tables are also presented in this chapter. The simulation results obtained using Matlab-Simulink environment and discussions of the results are presented in chapter five. Chapter six includes conclusions and suggestion for future work

CHAPTER TWO

LITERATURE REVIEW

In this chapter, a detailed literature review describing permanent magnet synchronous generator (PMSG) based wind turbine-generator systems will be presented. More specifically, the related previous studies and researches on the modeling, the control strategies, and the state of the converter topologies applied in PMSG-based wind turbine-generator systems will be discussed.

2.1 Wind Turbine Power Coefficient

A wind turbine extracts kinetic energy from the wind to drive the wind turbine rotor, which is connected to a generator producing electricity (Johnson G.L. 2006). The maximum power output from the wind turbine is limited by the power coefficient C_p which is a function of the tip speed ratio λ. C_p never exceeds 59.3%, the Betz Limit (Hau Erich 2006). In general, practically C_p is between 25% - 50% (Anaya-Lara O., et al. 2009b).

2.2 Wind Energy Generator System

In the book "Martin O. L. Hansen, Aerodynamics of Wind Turbine, Second Edition,2008", the authors comprehensively classified wind generators into three classes: direct coupled generator, doubly-fed induction generator and fully rated converter generator.

2.2.1 Direct-Coupled Generator

Fixed-speed squirrel-cage induction generators were widely employed for large wind turbine in 1980s, during which most of the technologies of wind turbines were direct coupled generator i.e. the wind turbine generator is directly coupled with the power grid. Due to the variation of the wind speed, the generator rotor speed is required to change slightly to balance the variation of the driving torque. The rotational speed of the generator is therefore not entirely constant. For a wound rotor induction generator, in order to produce magnetic field, it is necessary to provide extra power supply for the rotor circuit via a slip-ring. However the variation of the rotational speed is generally less than 1% due to the nature of small slip of induction generators (Anaya-Lara O., et al. 2009a), which is definition as the rate of the differential of the rotation speed of magnetic fields between the synchronous speed and rotation speed, divided by the synchronous speed (Shaw S.R. and Leeb S.B. 1999). Figure 2-1 illustrates a configuration of fixed-speed wind turbine, which consists of a squirrel-cage induction generator, bridge soft starter, a set of capacitor bank and a transformer.

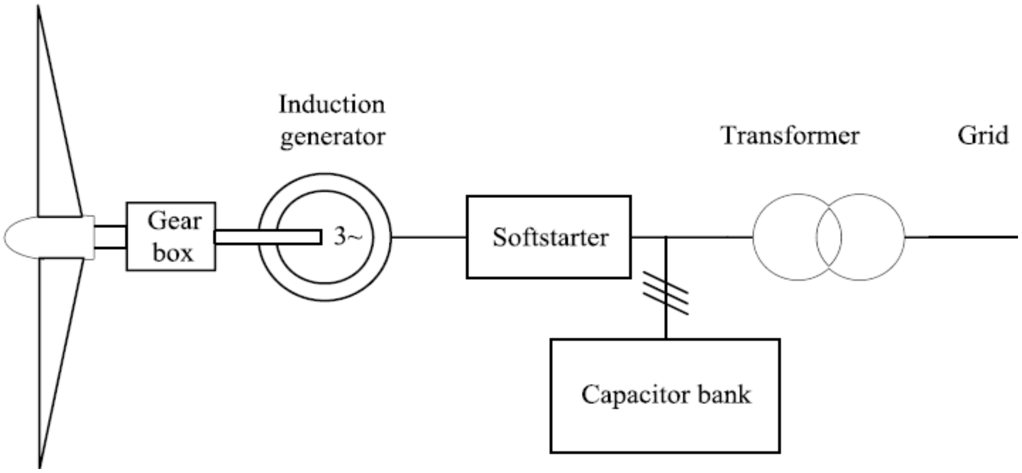

Figure 2.1 Fixed-Speed Wind Turbine System Based on IG [19]

In general, the squirrel-cage induction generator needs to consume reactive power. For this reason, the generator normally requires compensation for reactive power by connecting it to a capacitor bank. [18]

The advantages of this type of wind generation are: [18]

- Simple structure
- Low cost
- Easy to maintain
- Simple solution for grid connection
- High performance-to-price ratio

However, there are a number of problems with fixed-speed wind power generation. First, the wind turbine does not operate under optimal tip speed ratio (or maximum power point tracking) with wind speed variation. This causes low efficiency of the wind turbine. Furthermore the squirrel-cage induction generator has low efficiency and power factor, and it requires an extra power supply (reactive power) for excitation (Hau Erich 2006).

2.2.2 Doubly-Fed Induction Generator (DFIG)

The technology of doubly-fed induction generators is becoming more and more common due to the disadvantages of fixed speed induction generator. Variable speed DFIG is also an asynchronous generator, the common characteristics of doubly-fed and fixed-speed generator is that their stator windings can directly be connected to the grid. Power output from the stator of a DFIG can be delivered directly to the grid, and the generator rotor absorbs excitation current from the grid. As Figure 2.2 illustrated, the rotor of DFIG connects to the grid by means of power converter. The power converter is able to transfer power bi-directly, which means it can deliver power to the grid and is also able to absorb power from the grid, depending on the rotational speed of the generator (Anaya-Lara O., et al. 2009b).

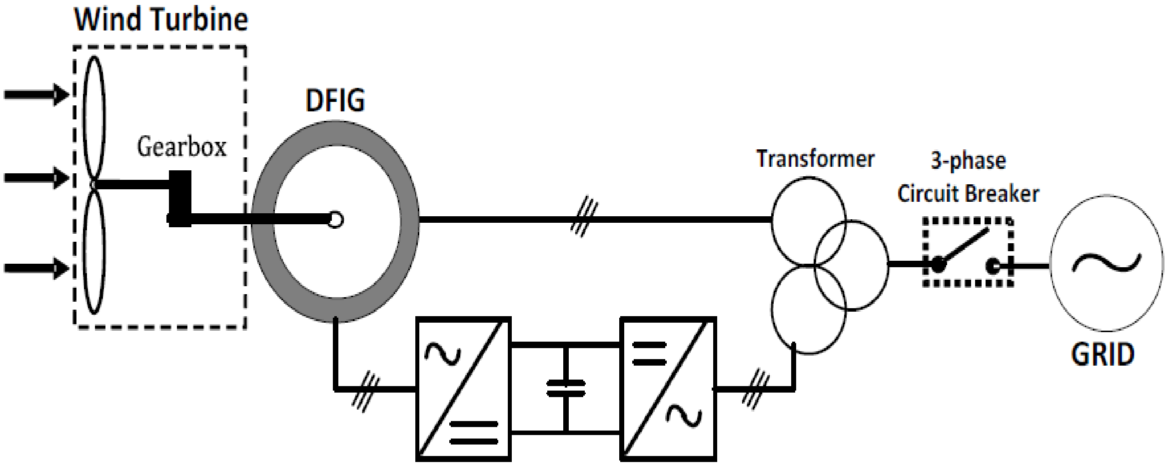

Figure 2.2 DFIG Indirect Drives Variable Speed Wind Turbines with Gearbox. [20]

Advantages of the DFIG-based wind turbine-generator system: [20]

- It has the ability of decoupling the control of the active and reactive power by controlling the rotor terminal voltages. Hence, the power factor control can be implemented in this system.
- The DFIG is usually a wound rotor induction generator, which is simple in construction

However, DFIG needs slip-rings and gearbox to synchronize the rotational speed of wind turbine generator and electrical generator which will require frequent maintenance. The gearbox adds to the weight, generates noise, needs regular maintenance and increases losses. The maintenance of the gearbox-generator system may be difficult, because the nacelle (protecting part) is located at the top of the tower.

2.2.3 Fully Rated Converter Generator

Figure 2-3 illustrates the characteristics of wind turbine configuration with fully rated converter. Full variable-speed WECs are very flexible in terms of which type of generator is used (Anaya-Lara O., et al. 2009b), it can be equipped with either an induction (SCIG) or a synchronous generator. The synchronous generator can be either a wound-rotor synchronous generator (WRSG) or a permanent-magnet synchronous generator (PMSG), the latter being the one mostly used by the wind turbine industry. In this configuration, the generator rotor is directly connected to the turbine rotor without any gearbox and the generator is interfaced with the grid/load using full scale AC-DC-AC power converters as shown in Fig.1.4. This configuration is most suited for full power control as it is connected to the grid through a power converter. The permanent magnet synchronous generators (PMSGs) used in this configuration are low speed generators with suitable number of poles and able to produce higher torque at low speed. The full-scale power converter can perform smooth grid connection over the entire speed range [3]. The power electronic converters used in this configuration have two primary goals: to act as an energy buffer (DC-link) for the power fluctuations caused by the wind turbine and for the transients coming from the grid side and enables the system to control active and reactive power [3].The back-to-back power inverter is rated to the generator power and its operation is similar to that in DFIG-based WECS. Its rotor-side ensures the rotational speed being adjusted within a large range, whereas its grid-side transfers the active power to the grid and attempts to cancel the reactive power consumption.

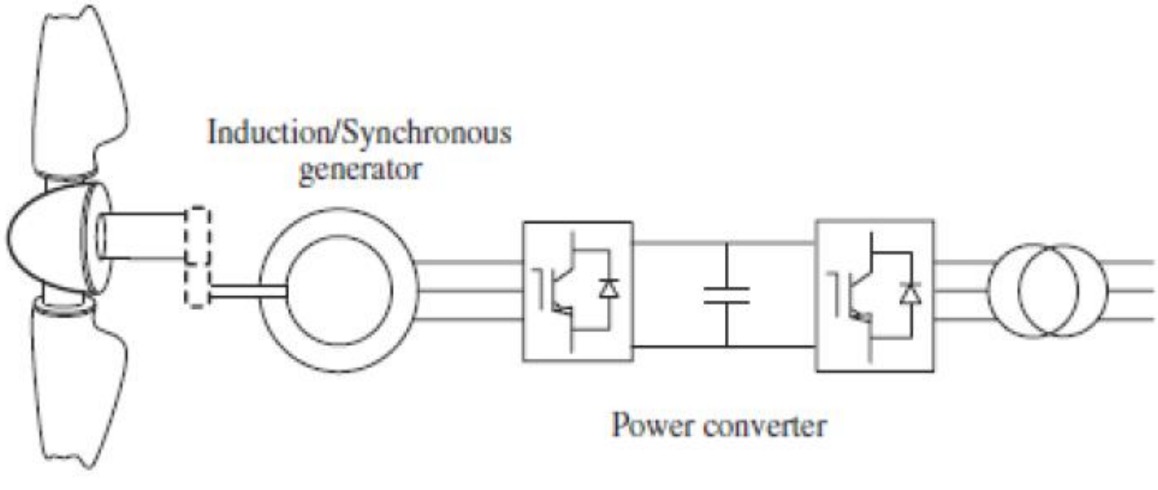

Figure 2.3 PMSG Fully Rated Converter Grid Connection [20]

The PMSG is considered, in many research articles, a good option to be used in WECS, due to its self-excitation property, which allows operation at high power factor and efficiency (Alatalo 1996). PMSG does not require energy supply for excitation, as it is supplied by the permanent magnets. The stator of a PMSG is wound and the rotor has a permanent magnet pole system. The salient pole of PMSG operates at low speeds, and thus the gearbox can be removed. This is a big advantage of PMSG-based WECS as the gearbox is a sensitive device in wind power systems. The same thing can be achieved using direct driven multi-pole PMSG with large diameter.

The advantages of fully rated converter grid connection are: [20][21]

- It allows variable-speed operation of the wind turbine, which enables maximum power point tracking (MPPT) between cut-in wind speed and rated wind speed.
- The PMSG can achieve full speed regulation.
- The PMSG makes it possible to avoid a gearbox; therefore, there is no mechanical stress issue when experiencing wind gusts.
- The PMSG does not need the slip-rings and brushes; hence, less maintenance will be needed. Therefore, a PMSG-based wind turbine will be more stable than a DFIG-based one.
- The PMSG can also achieve active power and reactive power control.
- The control schemes are relatively simple and easy to implement.

Disadvantages of the PMSG-based wind turbine-generator system [21]:

- The power converters of a PMSG-based wind turbine-generator system have a full-scale power rating, which means that the power converters will cause losses and generate high harmonic components.
- The permanent magnets run the risk of demagnetization at high temperature.

In this thesis the PMSG is chosen for the wind turbine generator, and the power output from the generator is fully rated power.

2.3 AC/DC Rectifier and DC/ DC Converter

There are a number of papers which discussed the strategy of power converters for PMSG wind turbines. The most popular control topology is the back-to-back converter as Figure 2.4 shows.

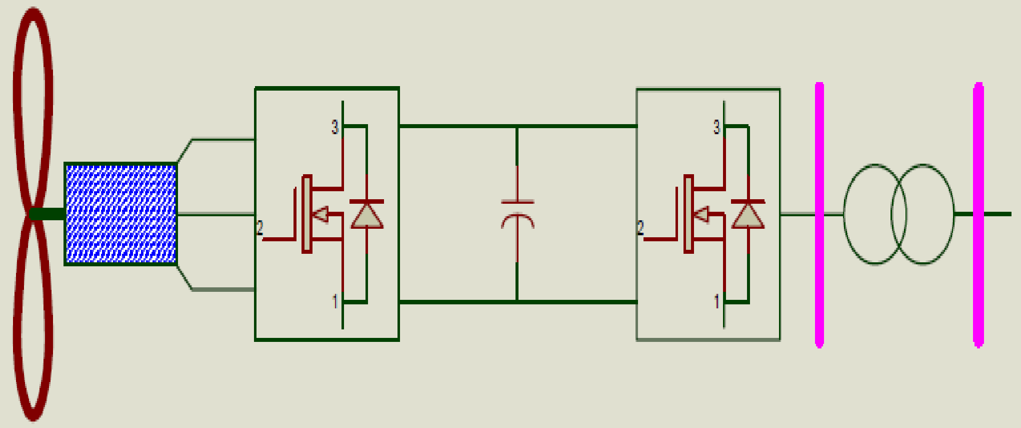

Figure 2.4 Wind Turbines PMSG with Back-to-Back Converter [19]

The characteristics of the back-to-back converter are that the converter utilizes active devices at both the generator side for the rectifier and the grid side for the inverter (Bharanikumar R., et al. 2010).

The advantages of back to back converter are as follows: [19]

- The rectifier is controllable, and
- Both rectifier and inverter bridges are composed of active IGBT devices, with the current are able to flow from either the generator to the grid or the grid to the generator.

The major disadvantage of back-to-back topology is: [19]

- The controller is complex and expensive because it requires 12-channel Pulse Width Modulation (PWM) signals for the rectifier and the inverter. For this reason, in a practical application, the control system requires at least two or more Micro-Controller Units (MCU), Digital Signal Processor (DSP), etc. to control the chips on the board.

A simple topology for wind turbine generation was introduced by Tarek Ahmed (Ahmed T., et al. 2004) and is illustrated in Figure 2.5, which consists of a diode bridge rectifier, with a DC link to an active IGBT inverter.

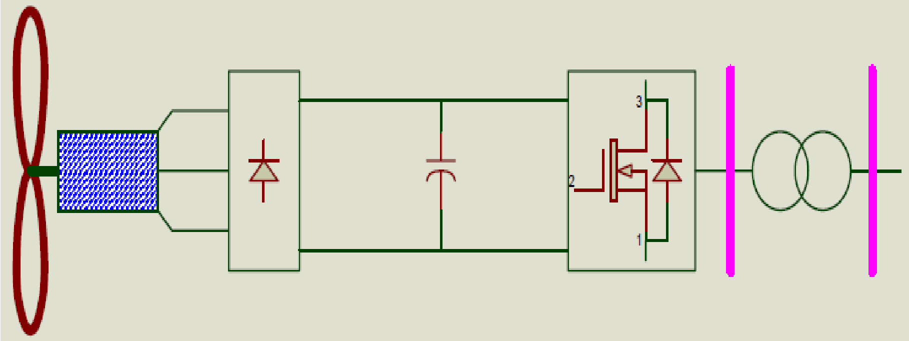

Figure 2.5 Wind Turbine Generators with Diode Rectifier [19]

Although this type of converter is simple and reliable, the power factor of the generator is low. [19] The other problem is that when the output voltage of the rectifier is lower than the grid, power cannot be injected to the grid. By summarizing the topology of back-to-back and diode rectifier, it is possible to insert a boost circuit between the diode rectifier and the inverter, in order to solve the issue of generator power factor, as shown in Figure 2.6. There have been a number of papers describing the inclusion of Power Factor Correction (PFC) with boost circuits, however only a few papers discuss it with the wind turbine controller (Belakehal S., et al. 2009; Bana Sharifian M.B, et al. 2009).

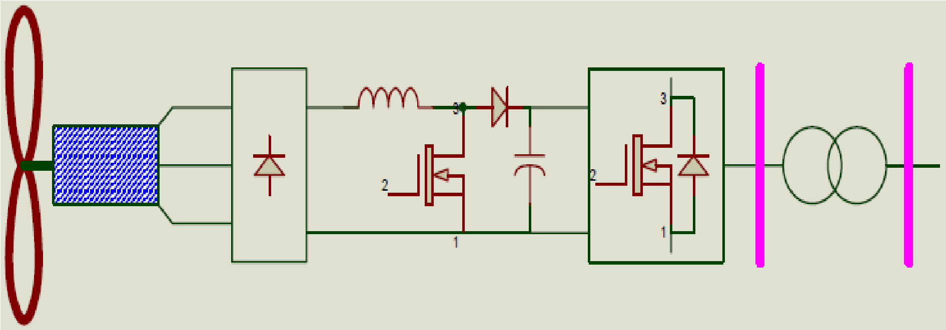

Figure 2.6 Wind Turbines with Diode Rectifier and Boost Circuit [19]

For this topology of converter, operation at relatively low wind speeds is possible due to the inclusion of the boost circuit. The boost circuit can maintain the DC bus link voltage at a constant value. The key principle that drives the boost converter is the tendency of an inductor to resist changes in current. When being charged it acts as a load and absorbs energy (somewhat like a resistor); when being discharged it acts as an energy source (somewhat like a battery). The voltage it produces during the discharge phase is related to the rate of change of current, and not to the original charging voltage, thus allowing different input and output voltages. This topology is utilized for the converter in this thesis.

2.4 Control Strategies for a Wind Turbine-Generator System

The control schemes for a wind turbine-generator system include the pitch angle control and maximum power point tracking control. The traditional control techniques and advanced control techniques for wind turbine-generator systems are reviewed in this section.

a) Pitch Angle Control

The pitch angle control is a mechanical method of controlling the blade angle of the wind turbine when the captured wind power exceeds its rated value or wind speed exceeds its rated value. In this way, pitch angle control is enabled to limit the maximum output power to be equal to the rated power, and thus protect the generator when the wind speed experiences gusts. The pitch angle controller is only activated at high wind speeds.

There is numerous pitch angle regulation techniques described in the literatures [23-25]. The conventional pitch angle control usually uses PI controllers. However, several advanced pitch control strategies were proposed. A new approach for the pitch angle control, which worked well for unstable and noisy circumstance, was presented in [26]. Another pitch control scheme was proposed in [27], in which a self-tuning regulator adaptive controller that incorporated a hybrid controller of a linear quadratic Gaussian neuro-controller and a linear parameter estimator was developed for the pitch angle control. In [28], the authors only applied a fuzzy logic pitch angle controller in a wind turbine-generator system to limit the power extracted from the wind above rated wind speed.

b) Maximum Power Point Tracking

In order to achieve the maximum power point tracking (MPPT) control, some control schemes have been presented. The MPPT control can be mainly divided into two types.

i. Conventional Control Schemes

The conventional control schemes can also be divided into current mode control and speed mode control, which depends on the setting of reference values. The reference values are the active power and electromagnetic torque for current mode control, and the rotational speed for the speed mode control. In [25], the author compared these two control strategies for dynamic transient analysis, and concluded that the current mode control has slow response with simple construction, while the speed mode control has fast response with complex construction. The discussions and limitations of these two control schemes were presented in [25].

In fact, the wind speeds in above conventional control schemes need to be exactly measured. However, the anemometer cannot precisely measure the wind speed because of the flow distortion, complex terrain and tower shadow influence. Hence, some studies on maximum wind energy tracking without wind velocity measurement had been developed in [26], [28].

ii. Intelligent Control Schemes

The intelligent control strategies usually apply the hill-climbing control and the fuzzy logic control to the maximum power point tracking control. The traditional hill-climbing control uses a fixed-step speed disturbance optimal control method to determine the speed, perturbation size and direction according to the changes in the power before and after sampling [26].

However, this control method is usually slow in speed because the step disturbance is fixed. Therefore, some improved hill-climbing control methods were proposed.

Fuzzy Logic Control in MPPT allows the control of systems whose parameters are incomplete, unknown or vague since it is a powerful tool and as a result, are difficult to model mathematically. This control strategy have the advantages of having robust speed control against wind gusts and turbine oscillatory torque, having superior dynamic and steady performances, and being independent of the turbine parameters and air density[25].

The advantages of using fuzzy logic controller are: [25]

- The control algorithm is universal and may be adapted to various systems with minimal adjustments.
- Low power and rotational speed fluctuation.
- Fast tracking time when operating above rated wind speed.
- The controller relies on the actual performance of the wind turbine rather than on theoretical data on turbine characteristics.
- Relatively unaffected by variations in turbine inertia and wind speed.

2.5 Overview of Fuzzy Logic System

Fuzzy logic was first proposed by Lotfi A. Zadeh of the University of California at Berkeley in 1965. He elaborated on his ideas in the paper in 1973 that introduced the concept of linguistic variables, which in this article equate to a variable defined as a fuzzy set [25]. Fuzzy logic emerged as a tool to deal with uncertain, imprecise, or qualitative decision-making problems.

Fuzzy systems are made of a knowledge base and reasoning mechanism called fuzzy inference engine. Fuzzy systems represents nonlinear mapping accompanied by fuzzy if-then rules from the rule base. Each of these rules describes the local mappings. The rule base can be constructed either from human expert knowledge or designer intuition [13].

A fuzzy controller consists of four main components as fuzzification, rule base, inference mechanism and defuzzification.

a) Fuzzification

Fuzzification is the process where the crisp quantities are converted to fuzzy (crisp to fuzzy), so that they are compatible with the fuzzy set representation in the rule base. The conversion of fuzzy values is represented by the membership functions. Membership functions are the graphical representation of linguistic variables.

According to fuzzy set theory the choice of the shape and width of membership function is subjective, but a few rules should be apply to make the computation simple like [16]

- All membership functions for a particular input or output should be symmetrical of the same width.
- A certain amount of overlap is desirable; otherwise the controller may run into poorly defined states, where it does not return a well defined output.
- The widths should initially be chosen so that each value of the universe is a member of at least two sets, except possibly for elements at the extreme ends. If, on the other hand, there is a gap between two sets no rules fire for values in the gap. Consequently the controller function is not defined.

b) Deffuzifiction

The fuzzy results generated cannot be used as such to the applications, hence it is necessary to convert the fuzzy quantities into crisp quantities for further processing. This can be achieved by using defuzzification process. The defuzzification has the capability to reduce a fuzzy to a crisp single-valued quantity or as a set, or converting to the form in which fuzzy quantity is present.

The defuzzification uses methods such as centre of gravity (centroid), max-membership principle, weighted average method, centre of largest area, and first of maxima or last of maxima to convert from the inference mechanism into the crisp values applied to the actual system. From this method centroid method is the most prevalent and physically appealing of all the defuzzification methods.

c) Rule Base

Rules form the basis for the fuzzy logic to obtain the fuzzy output. The rule-based form uses linguistic variables as its antecedents and consequents. The antecedents express an inference or the inequality, which should be satisfied. The consequents are those, which we can infer, and is the output if the antecedent inequality is satisfied. The fuzzy rule-based system uses IF–THEN rule-based system given by, IF antecedent, THEN consequent.

The basic properties of IF–THEN rules are:

a. Completeness: a set of IF–THEN rules is complete if any combination of input values result in an appropriate output value.
b. Consistency: a set of IF–THEN rules is inconsistent if there are two rules with the same rules-antecedent but different rule-consequents.
c. Continuity: a set of IF–THEN rules is continuous if it does not have neighboring rules with output fuzzy sets that have empty intersection.

d) Fuzzy Inference System

Fuzzy inference systems (FISs) are also known as fuzzy rule-based systems, fuzzy model, fuzzy expert system, and fuzzy associative memory. This is a major unit of a fuzzy logic system. The decision-making is an important part in the entire system. The FIS formulates suitable rules and based upon the rules the decision is made. This is mainly based on the concepts of the fuzzy set theory, fuzzy IF–THEN rules, and fuzzy reasoning. FIS uses “IF. . . THEN” statements, and the connectors present in the rule statement are “OR” or “AND” to make the necessary decision rules. The basic FIS can take either fuzzy inputs or crisp inputs, but the outputs it produces are almost always fuzzy sets.

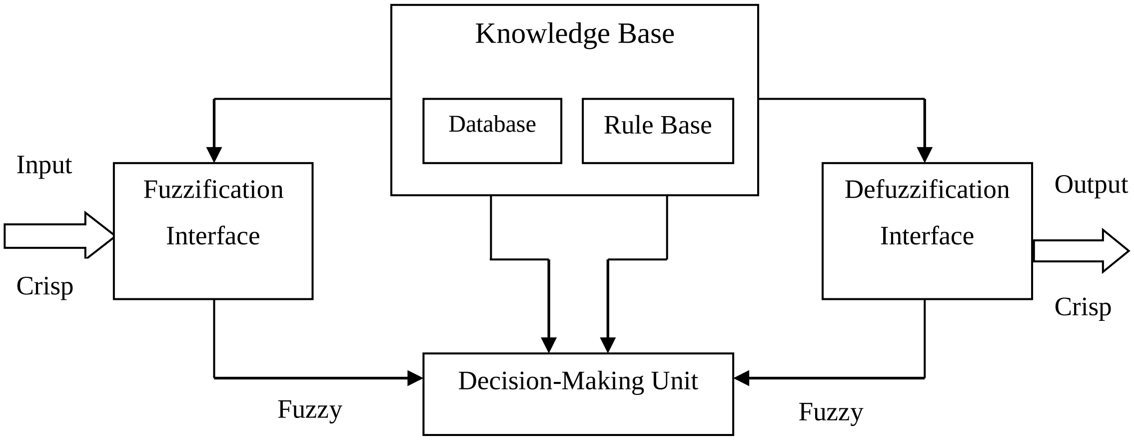

Figure 2.7 Fuzzy Inference Systems

2.6 Previous Works on Maximum Power Extraction of WECS

Different literatures have approached the research of MPPT of WECS in different ways and some of them are discussed here below briefly.

N. Surekha, and Dr. K. Ranjith Kumar [5] have proposed incremental conductance algorithm for maximum wind power extraction using permanent magnet synchronous generator. This algorithm is a mathematical optimization technique used to search for the local optimum point of a given function. This method is based on perturbing a control variable in small step-size and observing the resulting changes in the target function until the slope becomes zero. Since the P&O method does not require prior knowledge of the wind turbines characteristic curve, it is independent, simple, and flexible. However, it fails to reach the maximum power points under rapid wind variations if used for large and medium inertia wind turbines. Additionally, choosing an appropriate step size is not an easy task: though larger step-size means a faster response and more oscillations around the peak point, and hence, less efficiency, a smaller step-size improves efficiency but reduces the convergence speed [25, 33].

In the Paper by J. F. Gieras and M. Wing [15] has proposed a control method for tracking maximum power in a wind energy conversion system using online parameter identification. The online parameter identification was used to determine the optimum torque of the PMSG through back to back switched mode converters. In this controller the parameters (i.e. gains) of the controller are varied usually as a function of some exogenous variable in an attempt to compensate for the changes in the operating state of the plant through stepwise changes in the controller parameters. The drawback is that the parameter change may be rather abrupt across the region boundaries, which may result in unstable performance.

E. Koutroulis and K. Kalaitzakis [13] have proposed an Indirect Voltage Oriented Vector Control (IVOC) approach with conventional PI control to track the maximum power from wind through back to back converters. In this control scheme, the PM synchronous generator torque is controlled by controlling the *d*- and *q*-axes currents. Therefore, the generator torque is controlled indirectly by controlling *d*- and *q*-axes currents in the rotor reference frame. As the calculations are done in the rotor reference frame, a coordinate transformation is necessary in this scheme. This scheme is affected by generator parameter variations and introduces delay in the control system. It is well known that the relationship between maximum power from wind and wind speed is nonlinear. So it is not possible therefore to design a controller to operate satisfactorily at one operating state and expect it to perform equally well elsewhere without re-tuning it.

L. Whei-Min and H. Chih-Ming [10] has proposed the control scheme of a wind energy conversion system using fuzzy logic to track the maximum power from the wind turbine. In this case the boost DC / DC converter to control the output voltage of the rectifier (Vdc) is applied. Rectifier output voltage and current are measured and sent to the controller as input variables. The output of the fuzzy controller was given to the dc-dc converter to adjust the duty cycle. The main drawback to this system is fuzzy rule expert systems are difficult to acquire knowledge.

The aim of this thesis is to extract maximum power from wind energy conversion system using self tuning Fuzzy-PI controller. The output of the fuzzy controller was given to the dc-dc converter to adjust the duty cycle. When adjusting the duty cycle, the rotor speed of PMSG was controlled to get the maximum power.

CHAPTER THREE

MATHEMATICAL MODELING OF WECS

Modeling is a basic tool for analysis, such as optimization, project, design and control. Wind energy conversion systems are very different in nature from conventional generators, and therefore dynamic studies must be addressed in order to integrate wind power into the power system. Dynamic modeling is needed for various types of analysis related to system dynamics: stability, control system and optimization.

An overall model of wind energy system can be divided into following components:

1. Turbine and Drive Train Model
2. Generator Model
3. Converters Model
4. Control System Model

3.1 Wind Turbine (Aerodynamic) Modeling

The wind is characterized by its speed and direction, which are affected by several factors, *e.g.* geographic location, climate characteristics, height above ground, and surface topography. Wind turbines interact with the wind, capturing part of its kinetic energy and converting it into usable energy. The kinetic energy in air of an object of mass m moving with speed v is equal to:

$$K_E = \frac{1}{2} m v^2 \quad \text{(Nm)} \tag{3.1}$$

The power in the moving air, if we assume constant wind velocity, is:

$$P_{wind} = \frac{dK_E}{dt} = \frac{1}{2} \dot{m} v^2 \tag{3.2}$$

Where: $\dot{m}$ is the mass flow rate per second. For a stream flowing through a transversal area A the mass flow rate is $\rho A v$.

$$\dot{m} = \rho A v \tag{3.3}$$

Where: ρ is the air density.

When the air passes across an area A, such as the area swept by the rotor blades, the power in the air can be estimated as:

$$P_{wind} = \frac{1}{2}\rho A v^3 \tag{3.4}$$

Where: v is the wind speed.

3.1.1 Power Output from Ideal Wind Turbine [26]

The turbine can't extract all of the kinetic energy in the wind. If it did, the air would have to come to a complete stop behind the turbine, which, with nowhere to go. The downwind velocity shown in Figure 3.1, therefore, cannot be zero. Also, it makes no sense for the downwind velocity to be the same as the upwind speed since that would mean the turbine extracted no energy at all from the wind.

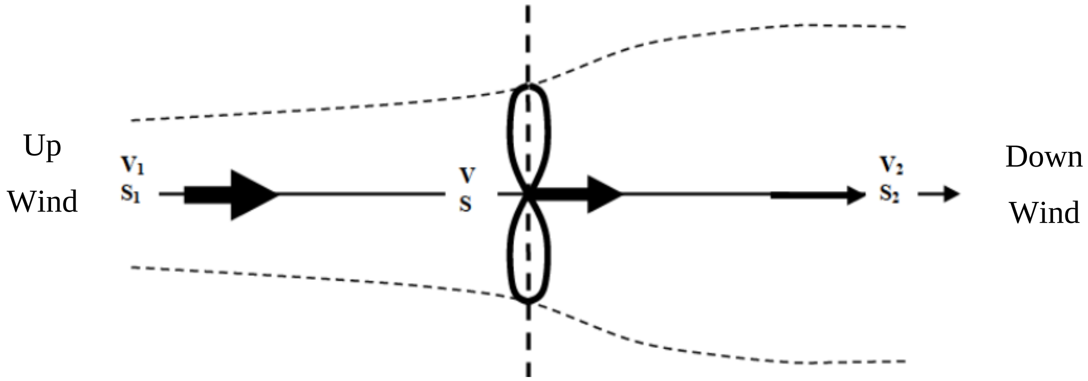

Figure 3.1 Air Steam around the Wind Turbine [26]

The wind speed passing through the turbine rotor is considered as V, with its value as V_1 upwind, and V_2 downwind at a distance from the rotor. Extraction of mechanical energy by the rotor occurs by reducing the kinetic energy of the air stream from upwind to downwind, or simply applying a breaking action on the wind. This implies that:

$$v_1 > v_2 \tag{3.5}$$

Consequently the air stream cross sectional area increases from upstream of the turbine to the downstream location, let say S_1=A_1 and S_2=A_2 implies:

$$A_1 < A_2 \tag{3.6}$$

If the air stream is considered as a case of incompressible flow, the conservation of mass or continuity equation can be written as:

$$\dot{m} = \rho A_1 v_1 = \rho A v = \rho A_2 v_2 = constant$$

From Euler's theorem, the force exerted by the wind on the rotor as:

$$F = ma = \frac{mdv}{dt} = \dot{m}\Delta v \tag{3.7}$$

$$F = \rho A v(v_1 - v_2) \tag{3.8}$$

The power content of the wind stream is:

$$P = \frac{dE}{dt} = \frac{Fdx}{dt} = FV \tag{3.9}$$

$$P = \rho A v^2(\mathrm{v}_1 - \mathrm{v}_2) \tag{3.10}$$

The power as the rate of change in kinetic energy from upstream to downstream is given by applying the low of conservation of energy as:

$$P_m = \frac{\Delta E}{\Delta t} = \frac{\frac{1}{2} m {v_1}^2 - \frac{1}{2} m {v_2}^2}{\Delta t} \tag{3.11}$$

$$P_m = \frac{1}{2}\dot{m}({v_1}^2 - {v_2}^2)$$

$$P_m = \frac{1}{2}\rho A v({v_1}^2 - {v_2}^2) \tag{3.12}$$

By equating the two power equations (3.10 and 3.12) we get:

$$v = \frac{1}{2}(v_1 + v_2) \tag{3.13}$$

This in turn suggests that the wind velocity at the rotor may be taken as the average of the upstream and downstream wind velocity.

So the mechanical power extracted becomes

$$P_m = \frac{1}{4}\rho A({v_1}^2 - {v_2}^2)(\, v_1 + v_2) \tag{3.14}$$

Comparing this mechanical power output with the power in the air stream that flows through the same cross-sectional area A, the ratio between the mechanical power extracted by the converter and the power contained in the air stream that passes through the same area is called the “power coefficient” C_p and can be represented as follows:

$$C_p = \frac{P_{mec}}{P_{wind}} \tag{3.15}$$

$$C_p = \frac{\frac{1}{4}\rho A({v_1}^2 - {v_2}^2(v_1 + v_2)}{\frac{1}{2}\ \rho A v^3}$$

The power coefficient can also be express in terms of the velocity ratio v_1/v_2:

$$C_p = \frac{P_{mec}}{P_{wind}} = \frac{1}{2}[1 - (\frac{v_2}{v_1})^2][1+\frac{v_2}{v_1}] \tag{3.16}$$

Wind turbine does not change the total amount of wind power due to many aerodynamic losses that depend on the rotor design and construction (number of blades, weight, stiffness, etc). Only a section of its kinetic energy is transformed to the rotor, while the remaining air leaving the wind turbine is carried away. Therefore real power formed by a rotor will be decided according to the energy transferred that would take place from the wind speed to the rotor. Therefore, the maximum theoretical efficiency that a wind energy converter can have is 59.3% and is known as Betz’s limit. It is good to mention that this value of the power coefficient was obtained for an ideal, frictionless flow converter.

$$C_{Pmax_{ideal}} = 0.593 \tag{3.17}$$

Where: $C_{Pmax_{ideal}}$ is the maximum theoretical power coefficient or known as Betz’s Limit.

3.1.2 Power Output from Practical Wind Turbine [27]

In real cases, the wind turbine will always have a smaller maximum power coefficient than the Betz factor. The extractable power from the wind for simulation purpose is therefore given by:

$$P_m = \frac{1}{2}\rho A v^3 C_p(\lambda, \beta) \tag{3.18}$$

Where: P_m is the mechanical power extracted from the wind, λ is tip speed ratio and β is blade pitch angle.

The power coefficient is not a static value as defined in the main question; it varies with the tip speed ratio of the turbine. Based on previous literature research, the basic formula of power coefficient C_p used for simulation purpose can be defined as a function of the tip-speed ratio and the blade pitch angle as follows:

$$C_p\,(\lambda,\beta) = c_1\left(\frac{c_2}{\lambda_i} - c_3\beta - c_4\right)e^{\frac{-c_5}{\lambda_i}} + c_6\,\lambda \tag{3.19}$$

$$\frac{1}{\lambda_i} = \frac{1}{\lambda - 0.08\beta} - \frac{0.035}{\beta^3 + 1} \tag{3.20}$$

Where c_1, c_2, c_3, c_4, c_5 and c_6 are 0.5176, 116, 0.4, 5, 21 and 0.0068 respectively. [27]

The fraction of the rotor blade tip speed and the unaffected wind velocity is expressed as tip speed ratio and is expressed as:

$$\lambda = \frac{blade\ tip\ speed}{wind\ speed} = \frac{r\omega_r}{V_w} \tag{3.21}$$

Where: r is the radius of the area covered by the blades; ω_r is the rotor angular speed at the wind turbine and V_w is the wind speed.

The mechanical torque from the wind turbine can be expressed as

$$\tau_w = \frac{p_m}{\omega_r} \tag{3.22}$$

Where: τ_w is the mechanical torque generated from wind turbine and ω_r is the rotor speed of the wind turbine.

3.1.3 Principles of Maximum Power Extraction

The power extracted from the wind is maximized when C_p is maximized. This optimal value of C_p occurs at a defined value of the tip speed ratio λ. The value of the tip speed ratio λ is constant for all maximum power points (MPPs). So, to extract maximum power at variable wind speed, the wind turbine should always operate at λ_{opt} in speeds below the rated speed. This occurs by controlling the rotational speed of the wind turbine to be equal to the optimum rotational speed. For each wind speed there is an optimum rotor speed where maximum power is extracted from the wind. Therefore, if wind speed is assumed to be constant the value of C_p depends on the rotor speed of the wind turbine. Thus, controlling the rotor speed controls the power output of the turbine. In addition, increasing the angle between the plane of rotation and the blade cross-section chord (pitch angle, β) will reduce the input power, and decreasing the pitch angle will increase the input power to the turbine generator. So for maximum power extraction the blade pitch angle should be kept at a fixed optimum value which is zero degree. When $\beta=0$, the blade is fully impacted by the wind velocity, and the wind turbine will capture the maximum power in the wind.

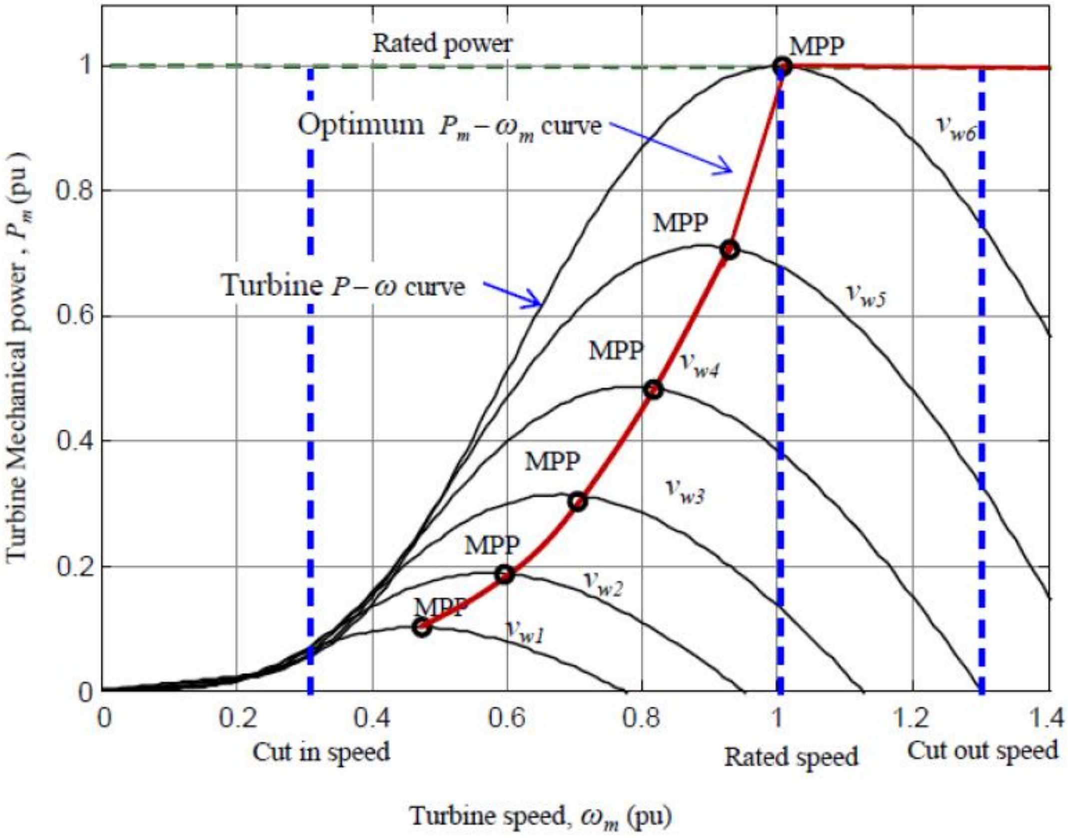

Figure 3.2 Turbine Power Characteristic with Maximum Power Point Tracking [28]

Since the precise measurement of wind speed is difficult, it is better to calculate the maximum power without measuring the wind speed as follows [28]:

$$P_{mppt} = \frac{1}{2}\rho\pi R^2 \left(\frac{\omega_r R}{\lambda_{opt}}\right)^3 C_{p-opt} \tag{3.23}$$

Where: λ_{opt} and C_{p-opt} are optimum values of tip speed ratio and power coefficient, respectively.

The maximum power is obtained if

$$C_p(\lambda) = C_p(\lambda_{opt}) = C_p max$$

$$P_{opt}(\omega_r) = \frac{1}{2}\frac{C_p max * \rho * \pi * R^5}{\lambda^3{}_{opt}}\omega_r{}^3{}_{opt} = K_{opt} * \omega_r{}^3{}_{opt} \tag{3.24}$$

The optimal torque is obtained from the rotation speed value given by

$$\tau_{opt}(\omega_r) = \frac{P_{opt}(\omega_r)}{\omega_r} = \frac{1}{2}\frac{C_p max * \rho * \pi * R^5}{\lambda^3{}_{opt}}\omega_r{}^2{}_{opt}$$

Thus, the following load torque has to be imposed to reach an optimal operation

$$\tau_{opt}(\omega_r) = K_{opt}\omega_{opt}{}^2 \tag{3.25}$$

In order to obtain maximum electrical power points, generator characteristics must be considered. To illustrate this fact, mechanical power produced by wind rotor (P_m) and electrical power produced by PMSG (P_g) versus ω_r, for various wind speeds, can be determined by: [27]

$$P_g = 3R_g * \left|I_g\right|^2$$

$$P_g(D) = \frac{\pi^2}{6}(1-D)R_L\frac{(K\varphi\omega_r)^2}{\left\{\frac{\pi^2}{18}(1-D)^2R_L + R_s{}^2 + X_s{}^2\right\}} \tag{3.26}$$

It has the extreme value, when the derivative of (3.26) becomes the zero, because D is within $0 \leq D \leq 1$, the function $P_g(D)$ has a single extreme point, coinciding with the wind turbine maximum power point, and the dc-to-dc converter duty cycle adjustment according to the control law of ensures convergence to the wind turbine maximum power point under any wind speed condition.

$$\frac{dP_g(D)}{dD} = 0$$

The maximum power point is pursued based on (3.27); duty ratio D_m which the electric power becomes maximum value is deduced. To calculate the parameters of the DC/DC boost converter the following maximum duty cycle equation is obtained,

$$D_m = \frac{\pi\sqrt{R_L}}{\pi\sqrt{R_L} + 3\sqrt{2\sqrt{R_s{}^2 + X_s{}^2}}} \tag{3.27}$$

Where D is the duty ratio, K is voltage constant, R_L is the load resistance, R_s is stator resistance and X_s is stator inductance.

3.2 Drive Train Modeling [29], [30]

The drive train (mechanical parts) of a wind turbine system in general consists of a blade pitching mechanism, a hub with blades, a rotor shaft (relatively long in wind energy conversion systems with asynchronous generators) and a gearbox with generator. The drive train model presented in this thesis includes the inertia of both the turbine and the generator. The moment of inertia of the wind wheel (hub with blades) is about 90% of the drive train total moment, while the generator rotor moment of inertia is equal to about 10%. At the same time, the generator represents the biggest torsional stiffness. The drive train system of the WTGS can be represented either by a three-mass model, two-mass model, single lumped-mass model or even a six-mass model. For precise transient analysis of WTGSs, a six-mass drive train model is needed. However, a six-mass drive train model increases the simulation time due to the complex and lengthy mathematical computation with small time-steps.

Therefore, reduced mass models are considered to simplify the computation while preserving a reasonable accuracy of transient processes. The structure of the model is presented in figure below.

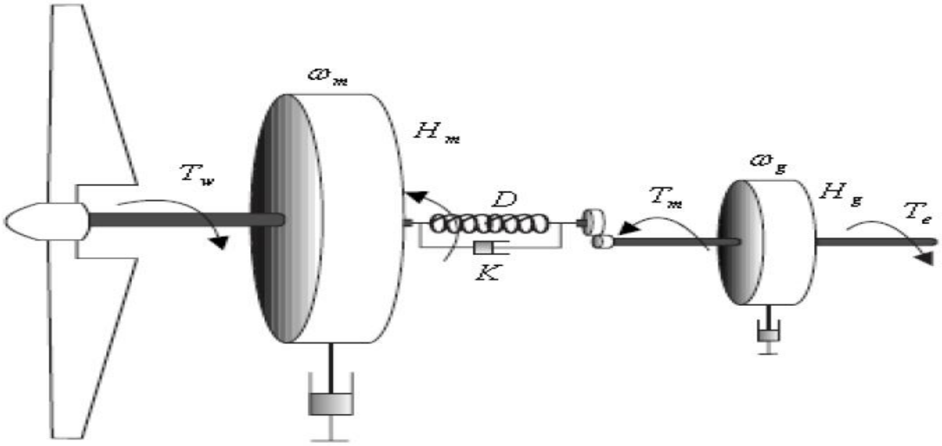

Figure 3.3 Two Mass Drive Train Model [29]

The equation of motion of the PMSG rotor based on Newton second law of rotation is given by:

$$H_g \frac{d\omega_g}{dt} = T_e + T_M \tag{3.28}$$

To account for the interaction between the wind turbine and the rotor, an additional equation describing the motion of the wind turbine shaft is adopted

$$H_m \frac{d\omega_m}{dt} = T_w - T_M \tag{3.29}$$

The mechanical torque T_m can be modeled with the following equation:

$$T_m = K\theta + D(\omega_g - \omega_m)$$

$$\frac{d\theta}{dt} = \omega_g - \omega_m \tag{3.30}$$

$$\omega_g = \frac{d\theta_r}{dt}$$

Where: H_m - Wind turbine inertia constant

H_g- electrical generator inertia constant

K- Shaft spring constant refer to high-speed shaft

D- Shaft mutual damping

θ_r- the rotor angle of the generator

T_w- wind turbine output torque

T_m - Input mechanical torque delivered to the generator

3.3 Mathematical Model of PMSG

Permanent magnet synchronous machines/generators (PMSMs/PMSGs) play key role in direct-drive wind power generation systems for transforming the mechanical power into electrical power.

A rigorous mathematical modeling of the PMSG is the prerequisite for the design of the machine control algorithms as well as the analysis of the steady-state and dynamic characteristics of wind energy conversion systems. Before developing the mathematical model of the PMSM, 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;

5. The stator windings are sinusoidally distributed along the air gap.

As the generator is directly coupled to the wind turbine rotor, the generator electrical angular frequency is derived from the mechanical rotor speed ω_r and the number of generator poles n_p.

$$f_e = \frac{n_p}{2} f_r = \frac{n_p}{2} \frac{\omega_r}{2\pi}$$

$$\omega_e = 2\pi f_e = \frac{n_p}{2} \omega_r \tag{3.31}$$

Where f_e and f_r are electrical and rotor angular frequency (in Hz) of PMSG, respectively and (ω_e) is the generator electrical angular frequency.

The generation system is composed of a PMSG and a full-rating power converter. In power system analyses, the magnetic flux distribution around the air gap of a synchronous generator is assumed to be sinusoidal. Therefore, the flux distribution linked with the stator coil is sinusoidal, and then the electromotive forces are also sinusoidal [31]. In fact, the induced voltage E_g generated by the permanent magnets can be expressed as:

$$E_g = 2\pi f_e \, \psi_m = \omega_e \psi_m \tag{3.32}$$

Where: ψ_m is the flux linkage of stator coil.

The state space relationship of the terminal voltages of the PMSM to the phase currents and the phase flux linkages due to the PMs and stator currents can be written as follows [32]

$$V_{as} = R_s i_{as} + \frac{d}{dt} \lambda_{as}$$

$$V_{bs} = R_s i_{bs} + \frac{d}{dt} \lambda_{bs} \tag{3.33}$$

$$V_{as} = R_s i_{cs} + \frac{d}{dt} \lambda_{cs}$$

Where V_{as} , V_{bs}, and V_{cs} are the instantaneous *a*, *b*, and *c* three-phase stator voltages, and i_{as} , i_{bs}, and i_{cs} are the instantaneous three-phase stator currents. Here, R_s is the stator winding resistance per phase, and again, λ_{as}, λ_{bs} , and λ_{cs} are the instantaneous flux linkages induced by the three-phase AC currents and the PMs.

To simplify the analysis of synchronous machinery models, the *dq0* Park's transformation is needed, and was first introduced by R. H. Park in 1929 [33]. The well-known machine model in dq-reference frame which is synchronously rotating with the rotor, where d-axis is aligned with the magnet axis and q-axis is orthogonal to d-axis, is usually used for analyzing the PM synchronous machine. In the three-phase systems like PMSMs, the phase quantities which include stator voltages, stator currents, and flux linkages, are time varying quantities. By applying Park's transformation, which is in essence the projection of the phase quantities onto a rotating two axes reference frame, the AC quantities are transformed to DC quantities which are independent of time.

The abc to $dq0$ transformation can be expressed in matrix form as follows.

$$\begin{bmatrix} u_d \\ u_q \\ u_0 \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos(\theta_r) & \cos(\theta_r - \frac{2\pi}{3}) & \cos(\theta_r + \frac{2\pi}{3}) \\ -\sin(\theta_r) & -\sin(\theta_r - \frac{2\pi}{3}) & -\sin(\theta_r + \frac{2\pi}{3}) \\ \frac{\sqrt{2}}{2} & \frac{\sqrt{2}}{2} & \frac{\sqrt{2}}{2} \end{bmatrix} \begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix} \tag{3.34}$$

The inverse Park's transformation is:

$$\begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos(\theta_r) & -\sin(\theta_r) & \frac{\sqrt{2}}{2} \\ \cos(\theta_r - \frac{2\pi}{2}) & -\sin(\theta_r - \frac{2\pi}{3}) & \frac{\sqrt{2}}{2} \\ \cos(\theta_r + \frac{2\pi}{3}) & -\sin(\theta_r + \frac{2\pi}{3}) & \frac{\sqrt{2}}{2} \end{bmatrix} \begin{bmatrix} u_d \\ u_q \\ u_0 \end{bmatrix} \tag{3.35}$$

Considering that under balanced conditions, V_0 =0, the voltage function of the PMSM in the dq-axes reference frame can be expressed as follows [33]

$$V_{ds} = R_s i_{ds} + L_d \frac{di_{ds}}{dt} - \omega_e L_q i_{qs}$$

$$V_{qs} = R_s i_{qs} + L_q \frac{di_{qs}}{dt} + \omega_e L_d i_{ds} + \omega_e \lambda_r \tag{3.36}$$

Where, V_{ds} and V_{qs}, are the instantaneous stator voltages in the dq-axes reference frame, i_{ds} and i_{qs} are the instantaneous stator currents in the dq-axes reference frame. Here, L_d and L_q , are the

d-axis and q-axis inductances, and ω_e is the electrical angular speed of the rotor, while, λ_r is the peak/maximum phase flux linkage due to the rotor-mounted PMs.

The equivalent circuits of the PMSM in the *dq-axes* reference frame can be drawn as shown in Figure below.

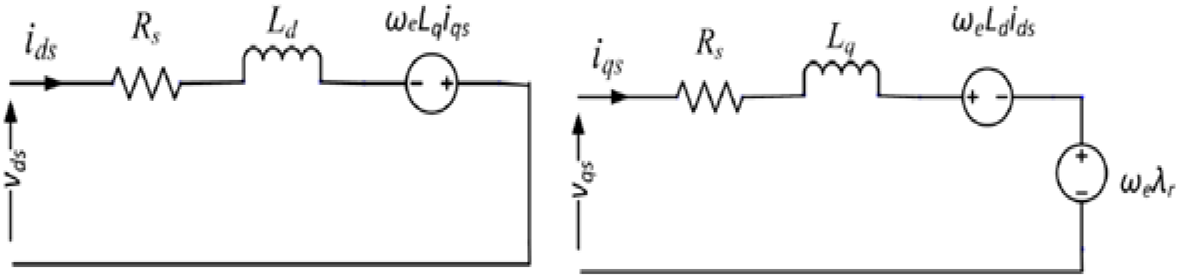

Figure 3.4 the Dq-Axes Equivalent Circuits of a PMSM [32]

For any PMSM, the electrical power input can be expressed in the *abc* reference frame as:

$$P_{abc} = V_{as}i_{as} + V_{bs}i_{bs} + V_{cs}i_{cs} \tag{3.37}$$

Or in the dq-axes reference frame as follows:

$$P_{dq} = \frac{3}{2}(V_{ds}i_{qs} + V_{qs}i_{qs}) \tag{3.38}$$

When an electric machine is used as a generator, a prime mover is needed to drive the generator. In wind energy applications the wind turbine is the prime mover of the generator. At steady state, the electromechanical torque of the machine should balance with the mechanical torque on the rotor shaft, created by the wind turbine.

Hence, the electromagnetic torque developed by a PMSM can be deduced as follows: [32]

$$T_e = \frac{3}{2}P\left[\lambda_m i_{qs} + \left(L_d - L_q\right)i_{qs}i_{ds}\right] \tag{3.39}$$

Where, p is the number of poles in the machine, λ_m is the magnetic flux, L_d is the direct axis inductance, and L_q is the inductance in quadrature.

3.4 Power Electronics

Power electronics is the application of solid state electronics to the control and conversion of electric power. The power conversion systems can be classified according to the type of the input and output power:

3.4.1 AC to DC Converters (Uncontrolled Rectifiers)

An uncontrolled rectifier is an unregulated converter that uses diodes to supply power to a dc circuit from an ac source. An uncontrolled rectifier gives a fixed dc output voltage for a given ac supply. Figure 3.5. below shows the circuit of a three phase, full-wave diode bridge rectifier.

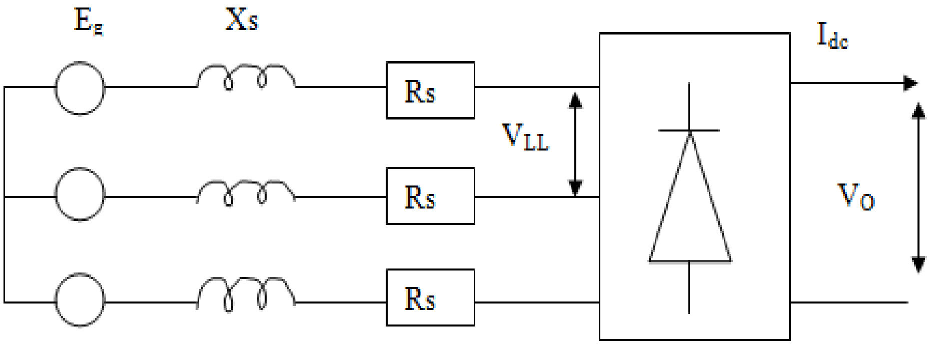

Figure 3.5 Connection Diode Rectifier Circuits to the Generator.

The average output voltage from the rectifier circuit is given by [34]

$$V_o = \frac{1}{\frac{\pi}{3}} \int_{-\frac{\pi}{6}}^{\frac{\pi}{6}} \sqrt{6} V_{LL} \operatorname{Cos}(\omega t)\, d(\omega t) \tag{3.40}$$

$$V_o = V_{rec} = \frac{3\sqrt{6}}{\pi} V_{LL}$$

Where $\boldsymbol{V_{LL}}$ is the phase to phase nominal voltage of the generator.

3.4.2 DC to DC Boost Converters

The purpose of a DC-DC converter is to supply a regulated DC output voltage to a variable-load from a fluctuating DC input voltage. In many cases the DC input voltage is obtained by rectifying a line voltage that is changing in magnitude.

A boost converter is one of DC-DC converter that can step up voltage while steeping down current from its input supply to its output load. The output voltage in Boost converters is generally controlled using a switching concept.

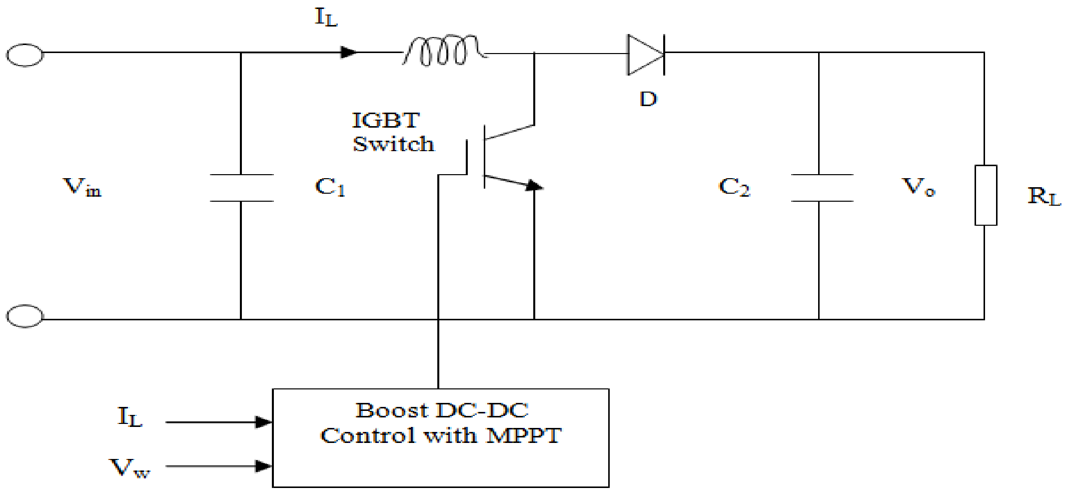

Figure 3.6 The Boost (Step Up) Converter.

The regulation of the average output voltage in a boost converter is a function of the on-time T_{on} of the switch, the pulse width, and the switching frequency f_s.

Define duty cycle (D) which depends on t_{on} and switching frequency f_s

$$D = \frac{t_{on}}{t_{on} + t_{off}} = \frac{t_{on}}{T} = t_{on} f_s \qquad (3.41)$$

During steady state operation the ratio between the output and input voltage is $\frac{1}{1-D}$. The output voltage is controlled by varying the duty cycle. Range of Duty Cycle: $0 < D < 1$.

$$t_{on} = DT$$

$$t_{off} = (1 - D)T$$

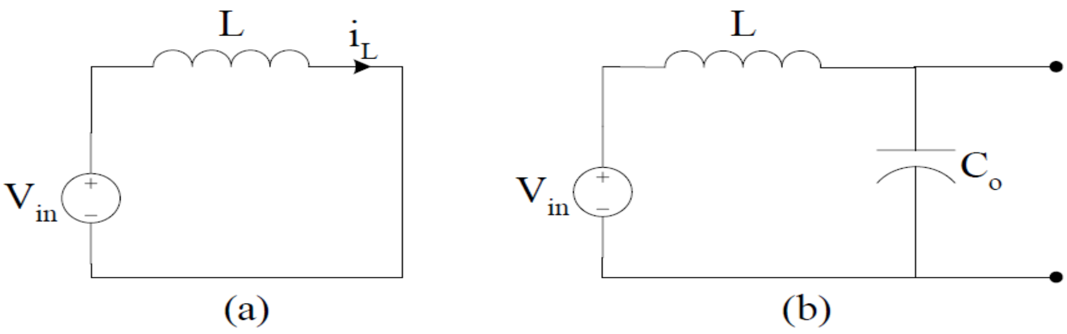

Figure 3.7 The Boost Converter When: (a) Switch on; (b) Switch off.

When the switch is on, the diode is reversed-biased, thus isolating the output stage. Input is disconnected from the output, no energy flows from input to output, output gets energy from capacitor. The equivalent circuit is shown in the figure 3.7(a).

In this case the inductor voltage is

$$V_L = V_i = L\frac{di_L}{dt} \Rightarrow \frac{di_L}{dt} = \frac{V_s}{L}$$

$$i_L(t) = \frac{1}{L}V_{in}t + I_L(0) \quad 0 \leq t \geq DT \tag{3.42}$$

Where $I_L(0)$ is the initial inductor current value at t=0, D is the duty cycle and T is the period.

For the next cycle, the power switches is open. The condition is depicted in figure 3.7(b). Because the inductor fully charged in the previous cycle, it will continue to force its current through the diode D to the output circuit and charge the capacitor. Inductor is discharging, diode is forward-biased. The output stage receives energy from the input as well as from the inductor.

In this case the inductor voltage is calculated as:

$$V_L = V_i - V_O = L\frac{di_L}{dt} \Rightarrow \frac{di_L}{dt} = \frac{V_i - V_o}{L}$$

$$i_L(t) = \frac{1}{L}(V_{in} - V_o)(t - DT) + I_L(DT) \qquad DT \leq t \geq T \tag{3.43}$$

In steady state the average inductor voltage is zero over one switching period, so

$$V_{LON}t_{ON} + V_{LOFF}t_{OFF} = 0$$

$$V_i\,DT + (V_i - V_o)(1 - D)T = 0 \tag{3.44}$$

$$V_o = \frac{1}{1-D} V_i$$

On the other hand, a major design aspect in a high power converter is the selection of the inductor. A small inductance value is preferred in order to reduce the inductor size and weight. A criterion that is simple but reasonable is to have the full (rated) load current operating under continuous conduction mode (CCM) boundary condition.

The minimum critical inductance value needed to insure the converter operates in CCM can be calculated as follows

$$L_{CR,BOOST} = \frac{V_o - V_{in}}{2P} \frac{{V_{in}}^2}{V_o} T_s \tag{3.45}$$

Also the output and input capacitor values found from the capacitors voltage ripple are given as

$$C_1 = \frac{\Delta I_L}{8\Delta V_{in}} T_s \tag{3.46}$$

$$C_2 = \frac{V_o D_m}{R_L \Delta V_o} T_s \tag{3.47}$$

Also the inductor ripple current is given by the equation

$$\Delta L_L = \frac{V_o - V_{in}}{2L} \frac{V_{in}}{V_o} T_s \tag{3.48}$$

Where, $\mathit{\Delta} V_0$ is output ripple voltage, $\mathit{\Delta} I_L$ is inductor ripple current, $T_{\,s}$ is switching time, f_s is switching frequency, R_L is load resistance, P is maximum power rating.

CHAPTER FOUR

CONTROLLER DESIGN

4.1 Control of Boost DC-DC Converter with Maximum Power Extraction

To extract optimum power under fluctuating wind speeds, the speed of the generator needs to be regulated by controlling the IGBT switch of the boost DC-DC converter. Figure 4.2 shows the proposed algorithm for maximum power extraction (MPE) from the variable speed wind turbine. This algorithm requires following steps and inputs:

- Measure wind speed v_w
- Calculate reference speed for maximum power extraction from

$$\omega_r{}^* = \frac{\lambda_{opt}}{R} V_w = K_w V_w \tag{4.2}$$

- Measure the rotor speed of the generator ω_r
- The error between reference and measured rotor speed is passed through Fuzzy-PI speed controller

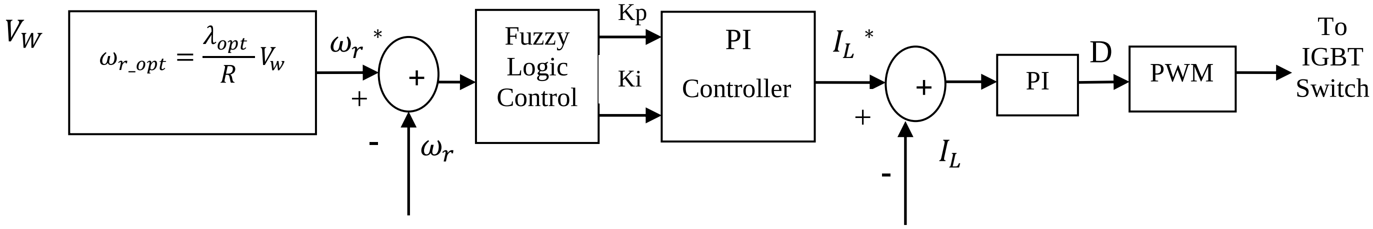

Figure 4.1 Proposed Maximum Power Extraction Algorithm Under Varying Wind Speed.

- The speed controller output will give the reference current $I_L{}^*$
- Measure the input inductor current to the boost converter I_L
- The error between reference and measured line currents is passed through proportional-integral (PI) to produce duty cycle, *D*.
- Finally the duty cycle, *D* is used to produce the required PWM pulses for the IGBT switch of the boost DC-DC converter.

4.1.1 PI Controller Design

The mathematical model of continuous-time linear proportional integral (PI) controller in position form is described as

$$u(t) = k_p e(t) + k_i \int_0^t e(t)dt \tag{4.3}$$

The corresponding discrete-time position form is described as

$$u(n) = k_p e(n) + k_i \sum_{i=0}^{n} e(i) \tag{4.4}$$

Where: K_p, K_i are the proportional gain and integral gain coefficients of the PI controller, respectively.

The coefficients of PI controllers (PI1 to PI2) for both speed and current controllers were obtained based on the trial-and-error approach. A lot of values were investigated for different system conditions, and finally, the values shown in table 4.1 are selected as best values.

Table 4.1 Proportional Integral Controller Gains

Controller	Speed Control(PI1)	Current Control(PI2)
Proportional Gain(k_P)	0.02	100
Integral Gain(k_i)	30	0.5

But the fixed PI controller is usually not the best under all kinds of states due to instability of the system input. The fuzzy logic controller is combined with conventional PI controller (Fuzzy-PI), and hence gain parameters of the PI controller can be adjusted based on tracking error.

4.1.2 Fuzzy Controller Design

A fuzzy logic controller (FLC) is designed to adjust and modify the proportional and the integral gains continuously based upon the operating condition.

The steps to design fuzzy logic control system are:

(1) Choosing the fuzzy controller inputs and outputs

(2) Partition the universe of discourse or the interval spanned by each variable into a number of fuzzy subsets, assigning each a linguistic label
(3) Assign or determine a membership function for each fuzzy subset
(4) Assign the fuzzy relationships between the inputs or states fuzzy subsets on the one hand and the outputs fuzzy subsets on the other hand, thus forming the rule-base
(5) Fuzzify the inputs to the controller
(6) Use fuzzy approximate reasoning to infer the output contributed from each rule
(7) Aggregate the fuzzy outputs recommended by each rule
(8) Apply defuzzification to form a crisp output

a. Fuzzfier Design

The error and deviation of error between the reference rotor speed and measured rotor speed are inputs to the fuzzy logic controller and are normalized to [-1, 1], the output signals are normalized to [-1, 1]. The input signals each consist of seven membership functions and the two outputs each consisting of seven membership functions.

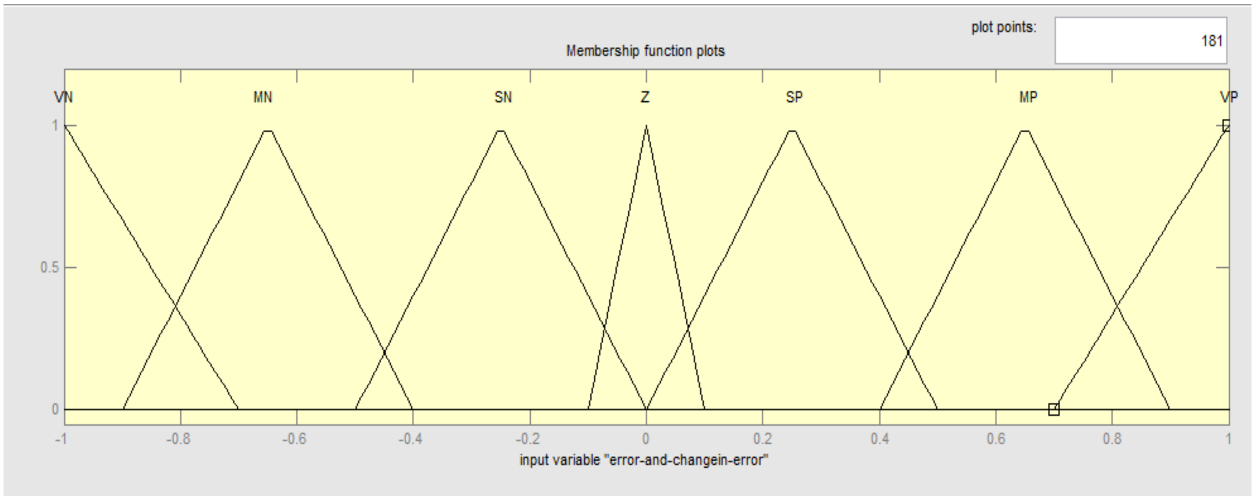

Figure 4.2 Input Membership Function for Error and Change in Error in Rotor Speed

Figure 4.3 is a graphical representation of the rotor speed error and change in error of rotor speed fuzzy membership functions. It assigns a crisp value's degree of membership to seven fuzzy linguistic values -- VN, MN, SN, Z, SP, MP, and VP for both inputs. The shape of the membership function and the universe of discourse for each function is found by trial and error after many simulations were done. The fuzzy inputs membership functions used are triangular type.

Table 4.2 Membership function universe of discourse of change in kp and ki

Δkp/Δki (Crisp Valve)	Degree of Membership (Fuzzy Relation)						
	NB	NM	NS	Z	PS	PM	PB
-1 to -.9	1	0	0	0	0	0	0
-.9 to -.75	1 to 0	0	0	0	0	0	0
-.8 to -.6	0	0 to 1	0	0	0	0	0
-.6 to -.4	0	1 to 0	0	0	0	0	0
-.45 to -.25	0	0	0 to 1	0	0	0	0
-.25 to -.05	0	0	1 to 0	0	0	0	0
-.15 to 0	0	0	0	0 to 1	0	0	0
0 to .15	0	0	0	1 to 0	0	0	0
.05 to .25	0	0	0	0	0 to 1	0	0
.25 to .45	0	0	0	0	1 to 0	0	0
.4 to .6	0	0	0	0	0	0 to 1	0
.6 to .8	0	0	0	0	0	1 to 0	0
0.75 to 0.9	0	0	0	0	0	0	0 to 1
0.9 to 1	0	0	0	0	0	0	1 to 0

b. Rule Base Formulation

We know that as per the control structure of a conventional PI controller in continuous time domain, the control action is $u(t) = k_p e(t) + k_i \int_0^t e(t)dt$. In the proportional term, control action is proportional to the "product of proportional gain k_p and error value" and in the integral term, it is proportional to "the product of the integral gain k_i and integral of the error". That means the proportional gain provides the control action effectively when the error is more (transient response) and the integral gain delivers efficiently when the system is operating near the set point value [13].

Hence the control method follows that when the rotor speed error is large, the proportional gain must be kept large and when the operating point is near the set point; the integral gain comes to action and reaches the maximum after reaching the steady state value. Fuzzy logic rules are written as per this control strategy such that the proportional gain (k_p) must be maximum when the error is large and should be started varying to the minimum when the system is near the set point. The integral gain (k_i) is varied such that its value will be minimum when the system operates away from the set point and attains maximum value when it operates near to the set point.

A fuzzy rule may contain fuzzy variables and fuzzy subsets characterized by membership function but they can be presented in different formats. In our systems, the rules are presented to the controller in a format similar to the one below.

End-user in a format similar to the one below,

1. If error is VN and change in error is VN then Δk_p is VP and Δk_i is VN
2. If error is Z and change in error is Z then Δk_p is Z and Δk_i is Z
3. If error is MP and change in error is MN then Δk_p is Z and Δk_i is Z
4. If error is SP and change in error is MN then Δk_p is SP and Δk_i is SN
5. If error is VP and change in error is VN then Δk_p is Z and Δk_i is Z

Table 4.3 Rule Table for kp

Kp		Error Derivative (Δe)						
		VN	MN	SN	Z	SP	MP	VP
Error(e)	VN	VP	VP	MP	MP	SP	SP	Z
	MN	VP	VP	MP	SP	SP	Z	SN
	SN	MP	MP	MP	SP	Z	SN	SN
	Z	MP	MP	SP	Z	SN	MN	MN
	SP	SP	SP	Z	SN	SN	MN	MN
	MP	SP	Z	SN	MN	MN	MN	VN
	VP	Z	SN	MN	MN	MN	VN	VN

Table 4.4 Rule Table for Ki

Ki		Error Derivative (Δe)						
		VN	MN	SN	Z	SP	MP	VP
	VN	VN	VN	MN	MN	SN	SN	Z
	MN	VN	VN	MN	SN	SN	Z	SP
	SN	VN	MN	SN	SN	Z	SP	SP

Error(e)	Z	MN	MN	SN	Z	SP	MP	MP
	SP	MN	SN	Z	SP	SP	MP	VP
	MP	SN	Z	SP	SP	MP	VP	VP
	VP	Z	SP	SP	MP	MP	VP	VP

c. Deffuzification

For this thesis the centroid defuzzification method to convert from the inference mechanism into the crisp values applied to the actual system is used. To obtain the fuzzified value, first the slopes of each membership function have to be determined and then line formula can be found easily. Based on the formula in equation 4.1, the fuzzy value can be converted into crisp quantities for further processing. The output of the fuzzy controller is multiplied by output scaling factors using trial and error method to get the final parameters and control signal.

The conversion is based on the following formula;

$$x^* = \frac{\int \mu_{\check{A}}(x).xdx}{\int \mu_{\check{A}}(x)dx} \qquad 4.1$$

Where, x^* denotes the defuzzified value and $\mu_{\check{A}}(x)$ is the membership of x in fuzzy set $\check{A}$.

The mathematical relations for some linguistic values are shown below.

For very negative (VN), the line equation is

$$Y1_{VN} = 3.34x + 4.43 \ldots.(-1.3, -1)$$

$$Y2_{VN} = -3.34x + 2.34 \ldots.(-1, -0.7)$$

Based on the above formula the defuzzified crisp value becomes

$$x_{VN}{}^* = \frac{\int_{-1.3}^{-1}(3.34\,x + 4.43)xdx + \int_{-1}^{-0.7}(-3.34\,x + 2.34)xdx}{\int_{-1.3}^{-1}(3.34\,x + 4.43)dx + \int_{-1}^{-0.7}(-3.34\,x + 2.34)dx}$$

$$x_{VN}{}^* = -1$$

For medium negative (MN), the line equation is

$$Y1_{MN} = 2.5x + 2.25 \ldots . (-0.9, -0.5)$$

$$Y2_{MN} = -2.5x - 0.25 \ldots . (-0.5, -0.1)$$

The defuzzified crisp value then becomes

$$x_{MN}{}^{*} = \frac{\int_{-0.9}^{-0.5}(2.5\,x + 2.25)xdx + \int_{-0.5}^{-0.9}(-2.5\,x - 0.25)xdx}{\int_{-0.9}^{-0.5}(2.5\,x + 2.25)dx + \int_{-0.5}^{-0.9}(-2.5\,x - 0.25)dx}$$

$$x_{MN}{}^{*} = -0.6$$

For small negative (SN), the line equation is

$$Y1_{SN} = 3.34x + 1.67 \ldots . (-0.5, -0.2)$$

$$Y2_{SN} = -5x \ldots \ldots \ldots \ldots . . \ldots . . (-0.2, 0)$$

The defuzzified crisp value then becomes

$$x_{SN}{}^{*} = \frac{\int_{-0.5}^{-0.2}(3.34\,x + 1.67)xdx + \int_{-0.2}^{0} 5\,x.xdx}{\int_{-0.5}^{-0.2}(3.34\,x + 1.67)dx + \int_{-0.2}^{0} 5\,xdx}$$

$$x_{MN}{}^{*} = -0.2$$

The same procedure is applied for the remaining membership function. The outputs defuzzification membership function is shown in figures 4.4.

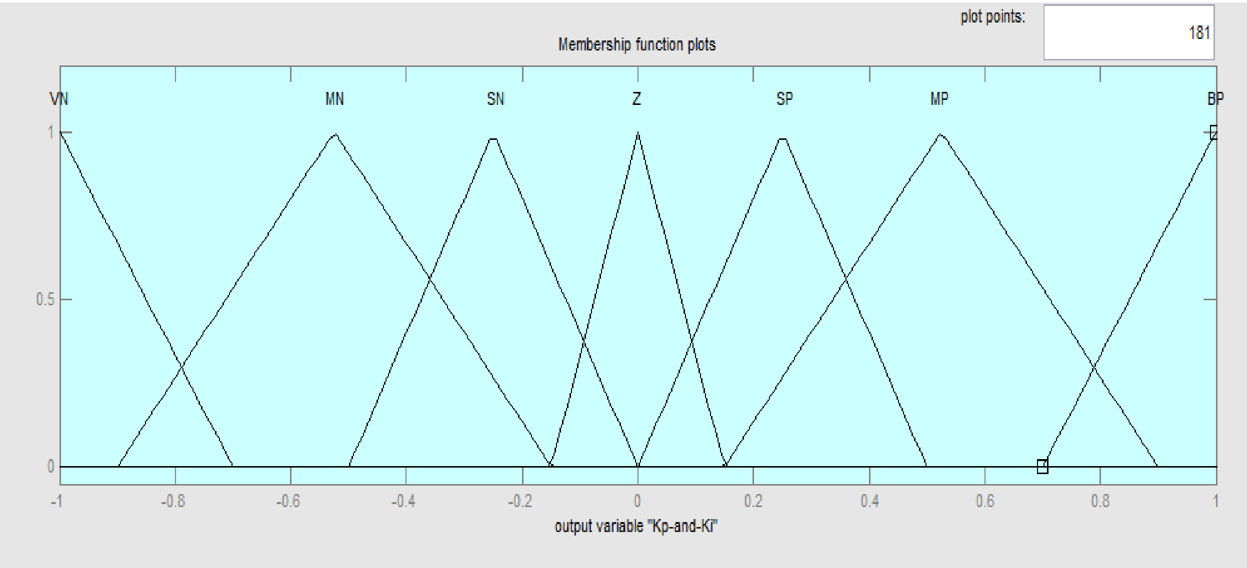

Figure 4.3 Output Membership Function for Change in K_p and K_i

Table 4.5 Linguistic Variable Descriptions and Output Crisp Values

Membership function	Range (fuzzy valve)	Defuzzified (Crisp value)
VN(Very Negative)	[-1.3 -0.7]	-1
MN(Medium Negative)	[-0.9 -0.1]	0.5
SN(Small Negative)	[-0.7 0]	-0.25
Z(Zero)	[-0.1 0.1]	0
SP(Small Positive)	[0 0.7]	0.25
MP(Medium Positive)	[0.1 0.9]	0.5
VP(Very Positive)	[0.7 1.3]	1

4.2 Simulink Model of WECS for Maximum Power Extraction

The overall Simulink model of the wind energy conversion system and control system is shown in Figure 4.5. The simulation model is developed based on permanent magnet synchronous generator (PMSG) and DC/DC boost converter. The parameters of the PMSG are given in Appendix A. The power converter and the controllers with maximum power extraction algorithm are included in the model. The load is set to be an equivalent resistor of 35 Ω and the chosen simulation type in Simulink is set as a discrete-type with a sample time of 0.2 μs.

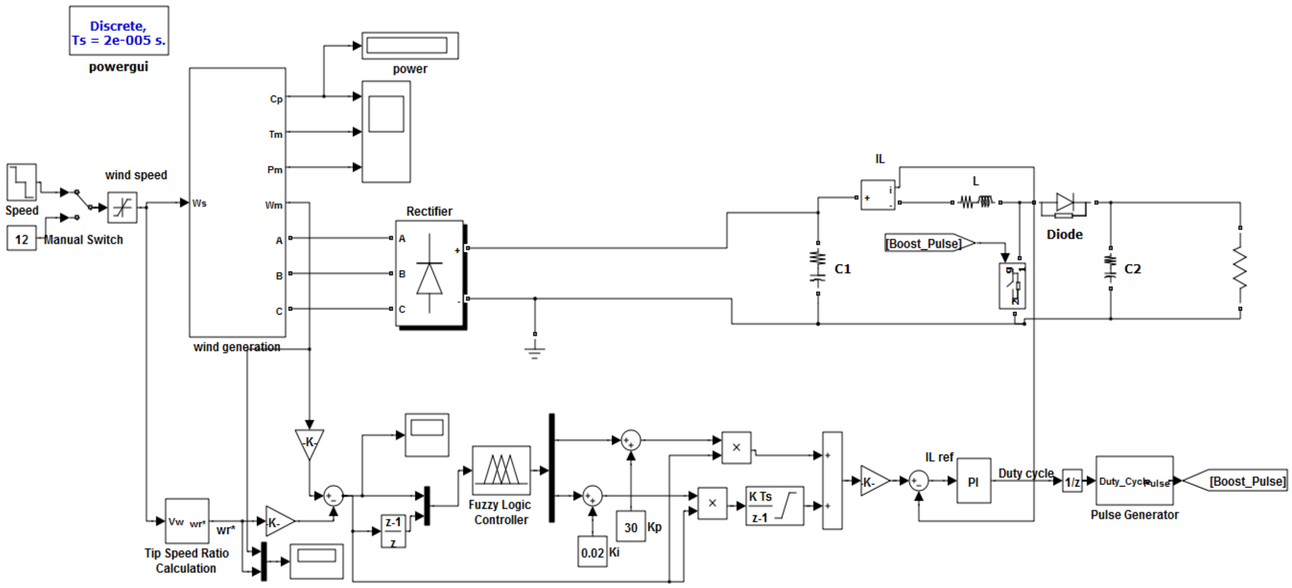

Figure 4.4 Overall Matlab Simulation Model

The simulation diagram for the main wind generation system with PMSG is shown in figure 4.6. A, B, and C are the three-phase output ports connected to uncontrolled rectifier. The ports related to torque are not on the same base. Output port of wind turbine is in per unit, while the input torque of PMSG is in its standard value. Base torque conversion is based on the nominal power of wind turbine and nominal angular speed of PMSG.

$$Power\ base\ for\ the\ Generator(PU) = \frac{p_{mec}}{p_{nom}}$$

$$p = \tau\omega \tag{4.5}$$

$$\tau = \tau_{p.u.}\frac{P_{nom}}{\omega_{nom}}$$

The nominal power of wind turbine is 8.5kW and the nominal angular speed of PMSG is 152.89rad/s.

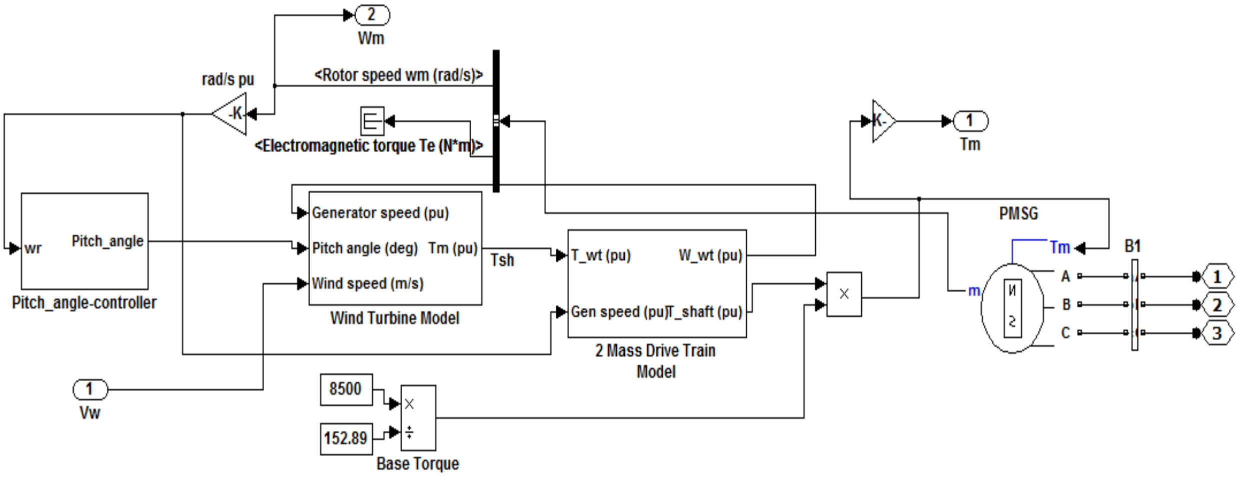

Figure 4.5 Simulation Diagram for the Wind Generation System

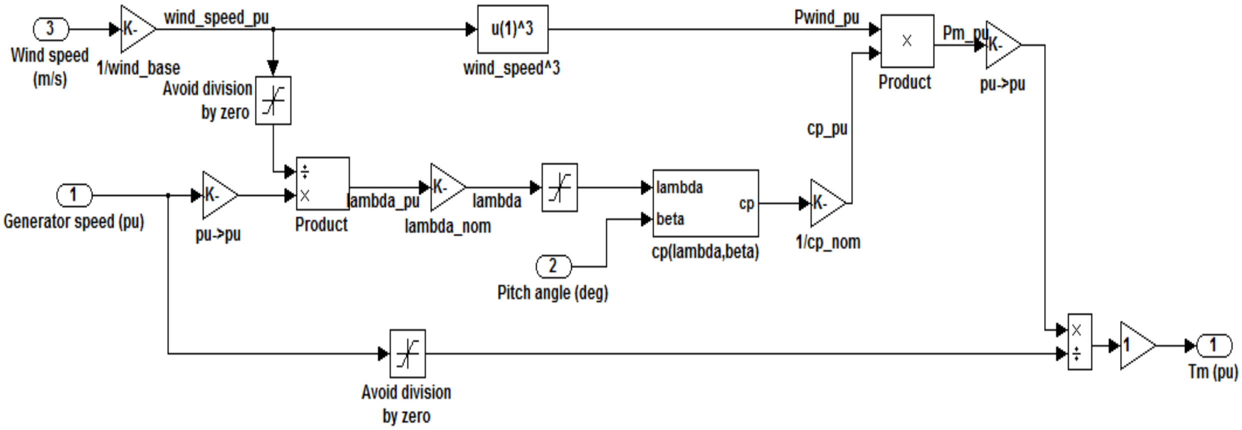

Figure 4.6 Simulation Diagram for the Wind Turbine Model

CHAPTER FIVE

SIMULATION RESULTS AND DISCUSSIONS

Two different wind speed profiles cases are considered in the simulation study to show the effectiveness of the proposed control strategy. In Case 1, simulation study is performed at rated wind speed. In Case 2, simulation study is performed by considering the wind speed as decreasing from rated wind speed to cut in wind speed. For both controllers the pitch angle should be kept at zero degree so that the wind turbine blade can be exposed fully with the incoming wind speed as a result the wind turbine can extract the maximum power available from the wind.

Case One: When wind speed is 12m/sec (Rated Wind Speed)

When the wind speed is 12m/s (rated wind speed), the simulation result is shown below.

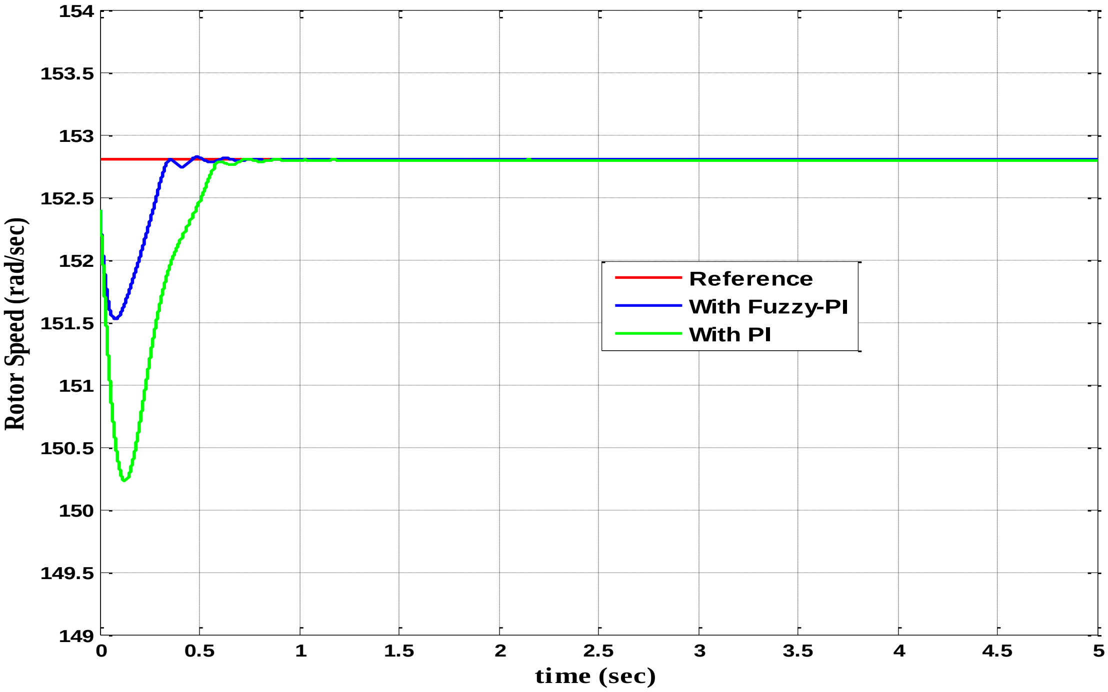

Figure 5.1 Rotor Speed for the Rated Wind Speed

The generator rated rotational speed is shown in the figure 5.1. From the simulation result it can be seen that, the generator operates under a constant rotation speed of 152.89rad/sec for both controllers (PI and Fuzzy-PI controllers) with almost same settling time (0.7sec) and zero steady state error at rated wind speed.

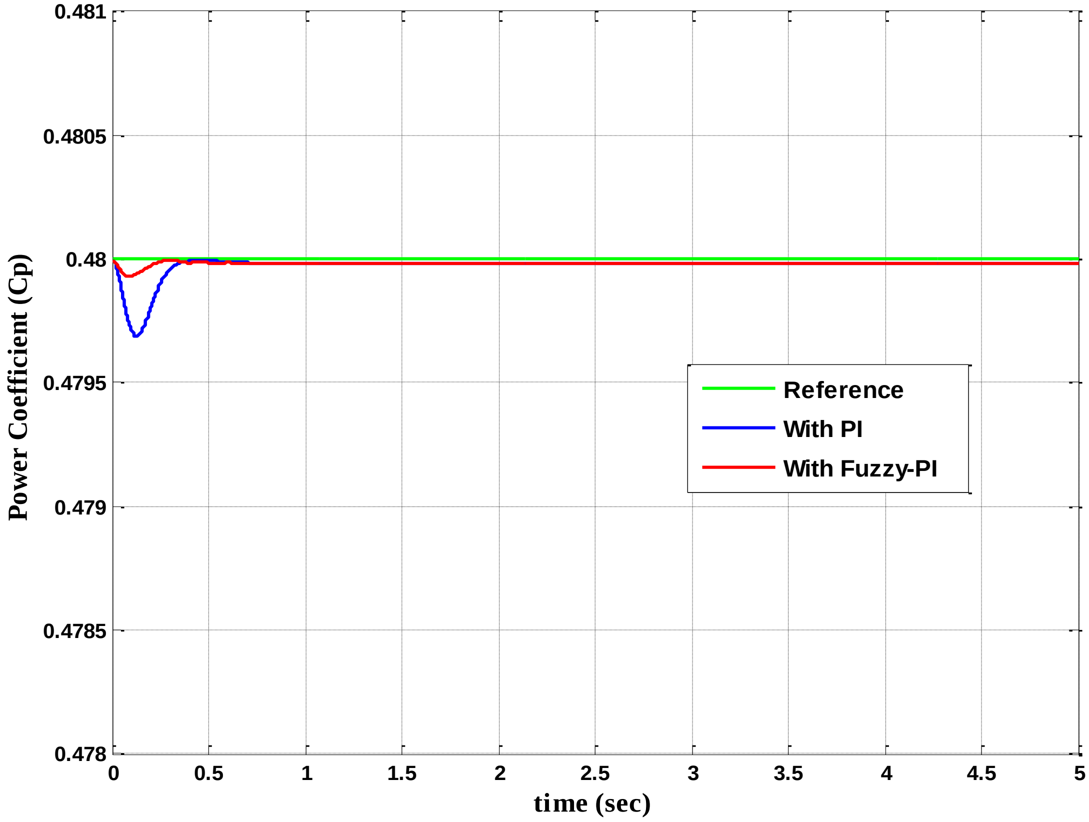

Figure 5.2 Optimum Power Coefficients (Rated)

The maximum power coefficient C_P is shown in the figure 5.2. To maximize the extracted energy, the wind turbine should operate at its maximum power coefficient. From the simulation result it is observed that the power coefficient remains constantly at the optimal value (0.48) for both controllers. If power coefficient remains constantly at the optimal value, it is guaranteed that the extracted energy will be maximized. It can be seen that both controllers give almost the same settling time (0.6sec) with almost zero steady-state error operation by responding its reference input at rated wind speed. From this it is conclude that the plant is stable with all controllers, a good transient and steady state performance is achieved when we employ both a fuzzy self tuning controller and PI controller at rated wind speed.

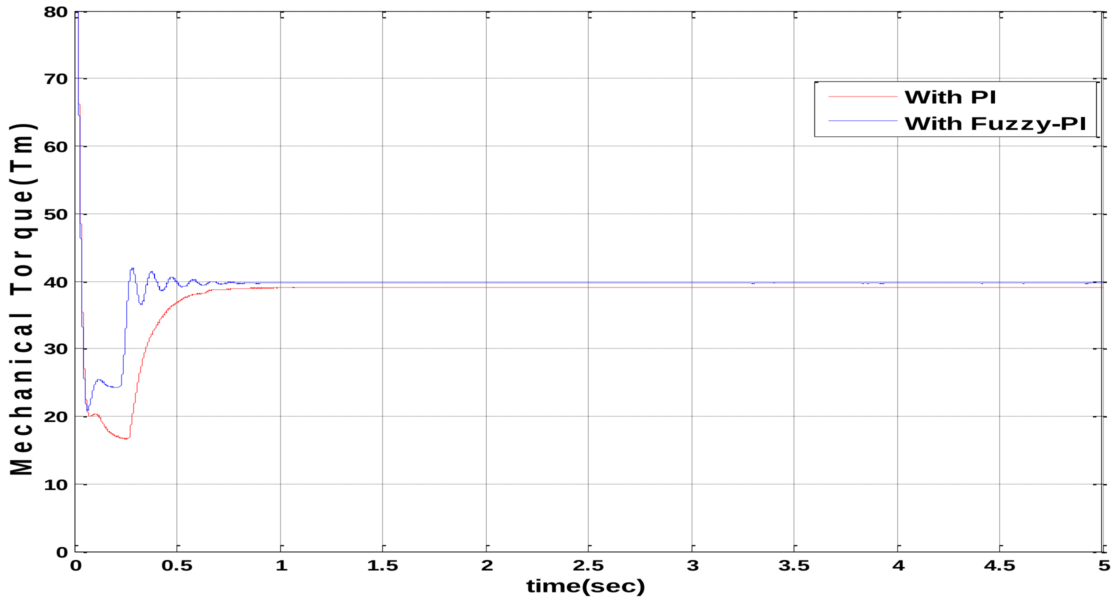

Figure 5.3 Mechanical Torque on the Rotor (Rated)

The mechanical torque is shown in the figure 5.3. It is further observed that that the fuzzy self tuning fuzzy controller tracks its reference torque (40W) with a settling time of 0.6sec and zero steady state error, whereas the torque output using PI controller slightly decrease from its reference.

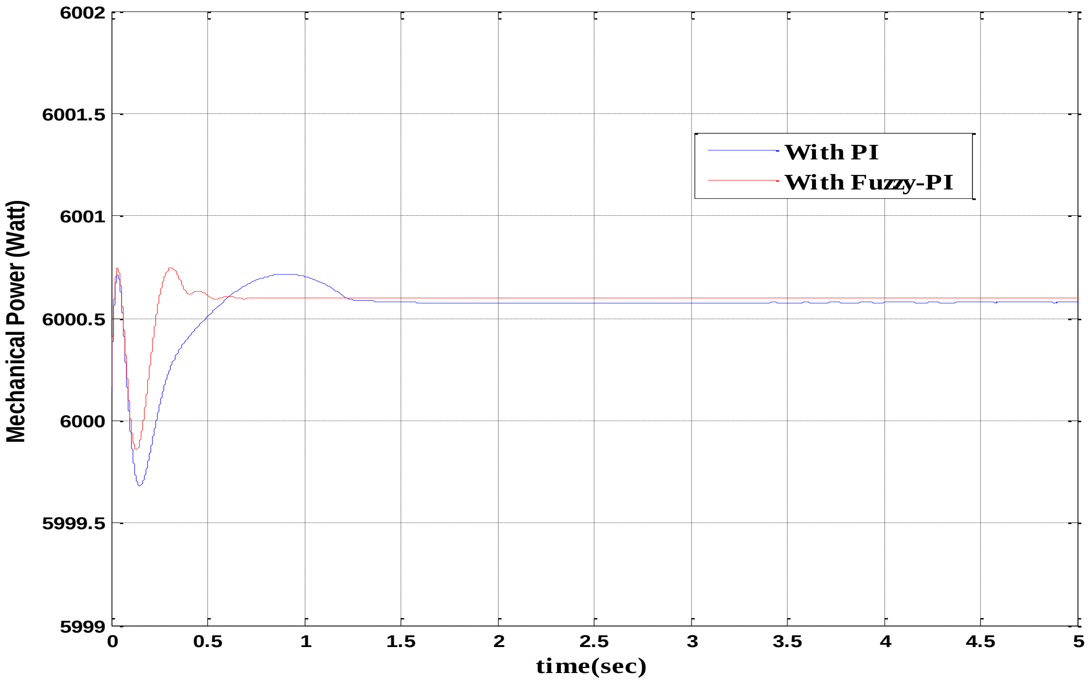

Figure 5.4 Maximum Power Extracted at Rated Wind Speed

The mechanical output power is shown in the figure 5.4. The overshoot and regulation time of the output power controlled by the two controllers at rated wind speed are shown in table 5.1. It can be seen that the control for achieving the generator mechanical power is realized and simulation result shows that the wind energy system operates steadily with 6kw rated reference power. The overshoot and regulation time of the self tuning fuzzy PI controller are less than that of the conventional PI controller.

Table 5.1 Overshoot and regulation times of the mechanical power extracted when wind speed is 12m/sec

Controller	Overshoot (%)	Settling Time (sec)	Steady State Error (%)
PI	0.1	1.4	0%
Fuzzy-PI	0.08	0.6	0%

Case Two: When the wind speed profile is changed that means when wind speed profile is goes from rated wind speed to cut in wind speed. If the wind turbine speed can keep track of the wind speed changes, maximum power could be extracted.

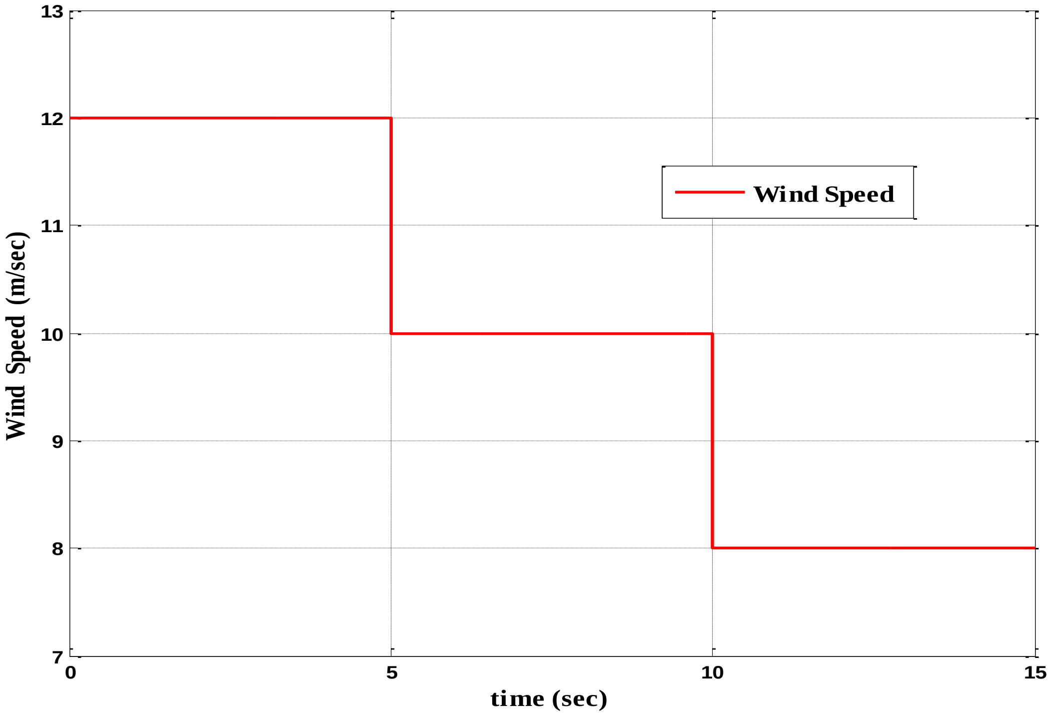

Figure 5.5 Wind Speed Profile Two

Figure 5.6 shows the rotational speed tracking of the wind turbine generator with its reference speed, the MPPT reference speed is calculated by an MPPT algorithm discussed in section 4.2 of chapter 4. Optimum rotational speed, ω_{opt} changes from a certain wind speed to another. The fuzzy logic controller is used to search the optimum rotational speed which tracks the maximum power point at variable wind speeds. Figure 5.6 shows the variation of the actual and reference rotational speed as a result of the wind speed variation. At a certain wind speed, the actual and reference rotational speed have been estimated and this agree with the power characteristic of the wind turbine shown later in figure 3.2. I.e. the WT always operates at the optimum rotational speed which is found using self tuning FLC. It is seen that according to the wind speed variation the generator speed varies and that its output power is produced corresponding to the wind speed variation. The self tuning fuzzy logic controller works well and it gives the good tracking performance for the optimum rotational speed and the maximum output power point as compared to PI controller.

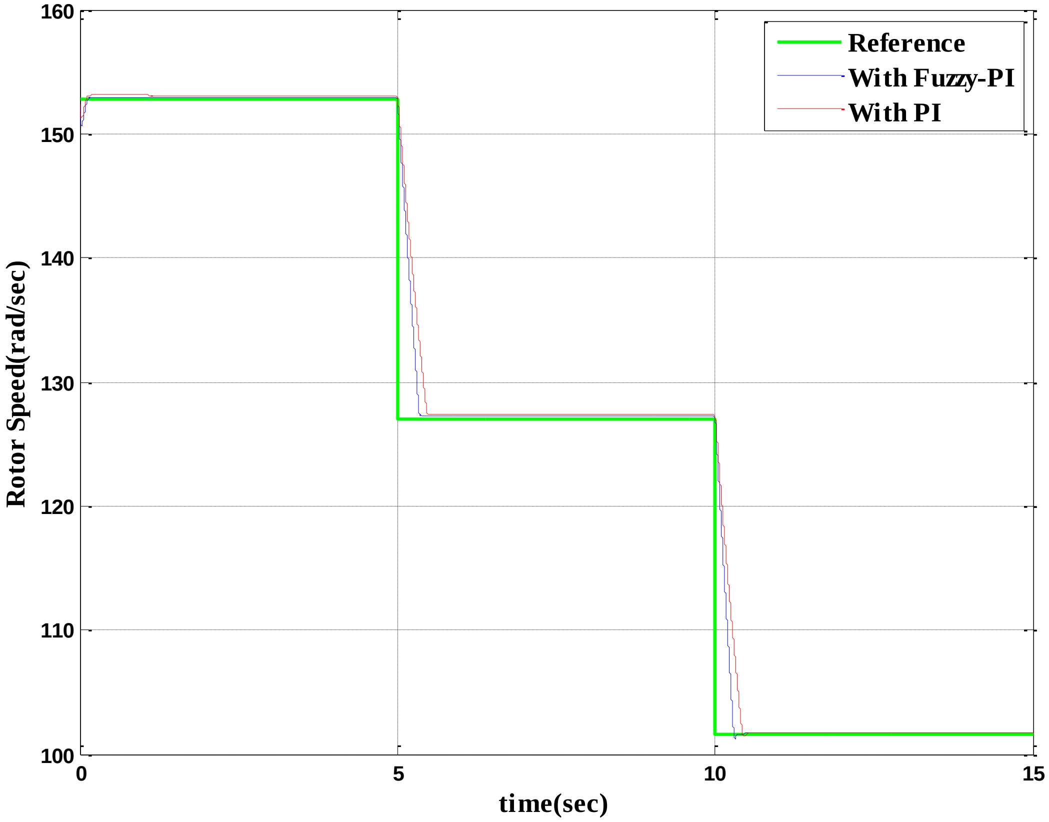

Figure 5.6 Rotor Speed for Wind Speed Profile Two

Figure 5.7 shows the wind turbine maximum power coefficient C_P of wind. The power extracted from the wind is maximized when the wind turbine is operating at the maximum power coefficient C_p. In Figure 5.7, the power coefficient of this wind turbine can be seen kept at the optimal value of 0.48 whenever the wind speed is changed.

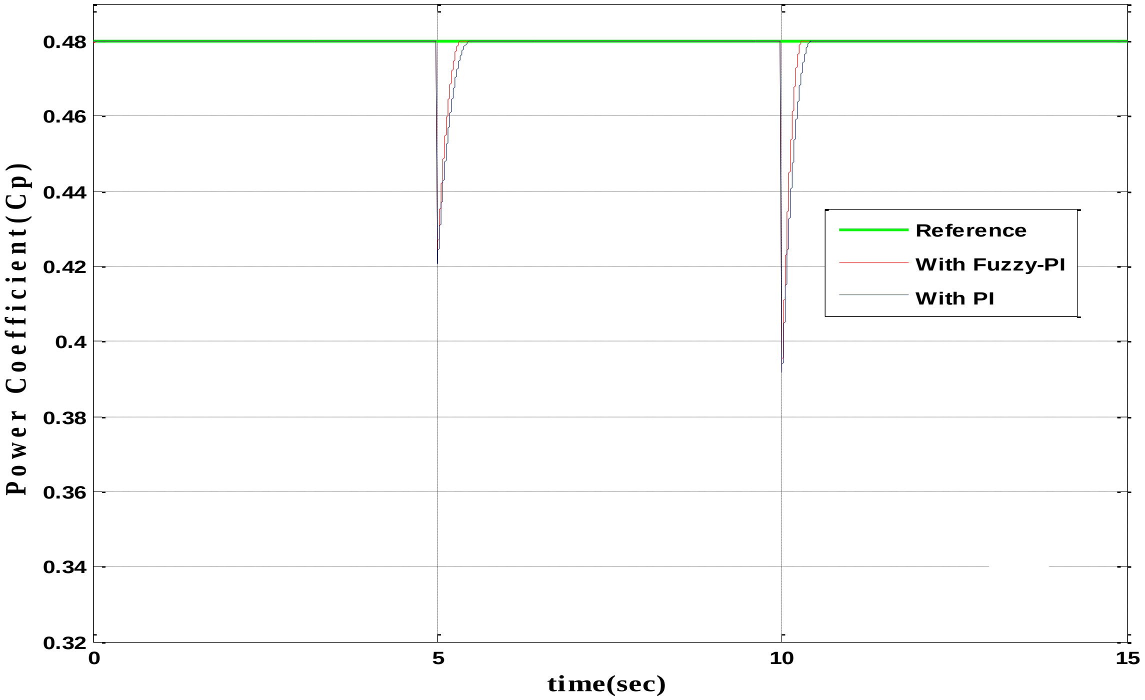

Figure 5.7 Power Coefficients for Wind Speed Profile Two

Figure 5.8 shows the wind energy conversion system simulated amount of power that has been extracted from the turbine as the wind speed varies. The primary aim of the PMSG control technique is to extract as much power as possible from the wind. For each wind speed there is one rotor speed that will yield maximum power, making the system monotonic. It can be seen that when the wind speed was 12m/s between 1s to 5s, the generator is controlled to track maximum rated turbine power of 6KW, while between the time interval of 5s to 10s when the wind speed changes to 10m/s the controller tracks the electromagnetic torque and produce maximum turbine power of 3.5KW, and finally when the wind speed changes to 10s to 15s the turbine can produce a maximum mechanical power of 1.9KW. It is seen that the turbine mechanical power follow the optimum power curve with a slight overshoot when wind speed changes and the generator can extract maximum power under variable wind speeds.

Table 5.2 Overshoot and regulation times of the mechanical power extracted when wind speed is below rated

Wind Speed	Overshoot (%)		Settling Time (m/sec)		Steady State Error (%)	
	PI	Fuzzy-PI	PI	Fuzzy-PI	PI	Fuzzy-PI
12	0.2	0.09	1.4	0.6	0	0
10	0.1	0.07	6.1	5.4	0	0
8	0.09	0.01	11.2	10.5	0	0

The overshoot given by the self tuning fuzzy PI controller is reduced to 0.09% from 0.2% while the regulation time is reduced to 0.6 s from 1.4s from the PI controller, when the wind speed is 12 m/s. The overshoot given by the self tuning Fuzzy PI controller is reduced to 0.07% from 0.1% and 0.01% from 0.09% in comparison with the PI controller while the regulation time is reduced to 5.4s from 6.1s and 10.5s from 11.2 from the PI controller, when the wind speed changes suddenly from 12 m/s to 10 m/s and 10m/s to 8m/s respectively. Generally the control effect of self tuning fuzzy PI controller can be clearly observed to have less overshoot and faster regulation.

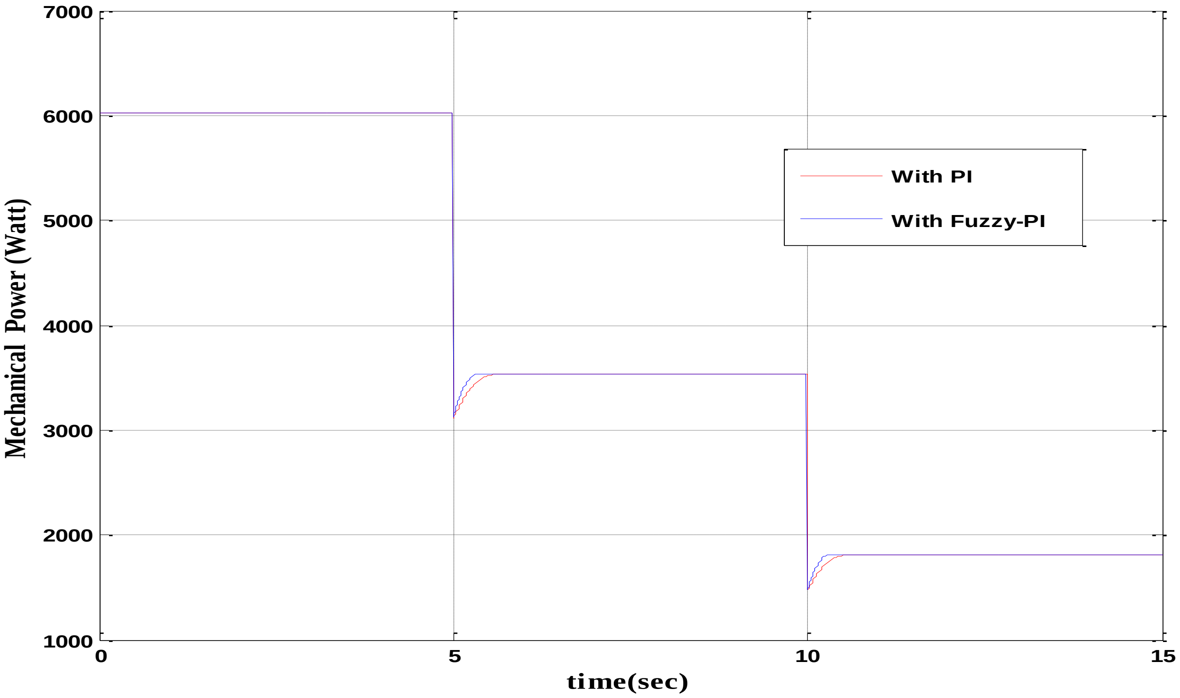

Figure 5.8 Maximum Power Extracted for Wind Speed Profile Two

Figure 5.9 shows the generator torque responses under varying wind speed. From the graph, we can see that when wind speed varies, there is some delay in mechanical torque due to the mechanical inertia of the generator and inductance or capacitance existed in DC-DC boost converter circuit. From the above figure it is conclude that, the control effect of Fuzzy-PI controller can be clearly observed to have less delay time and faster regulation. It is evidenced that the Fuzzy PI controller can give better performance than a PI controller when there is a sudden change of wind speed in power production.

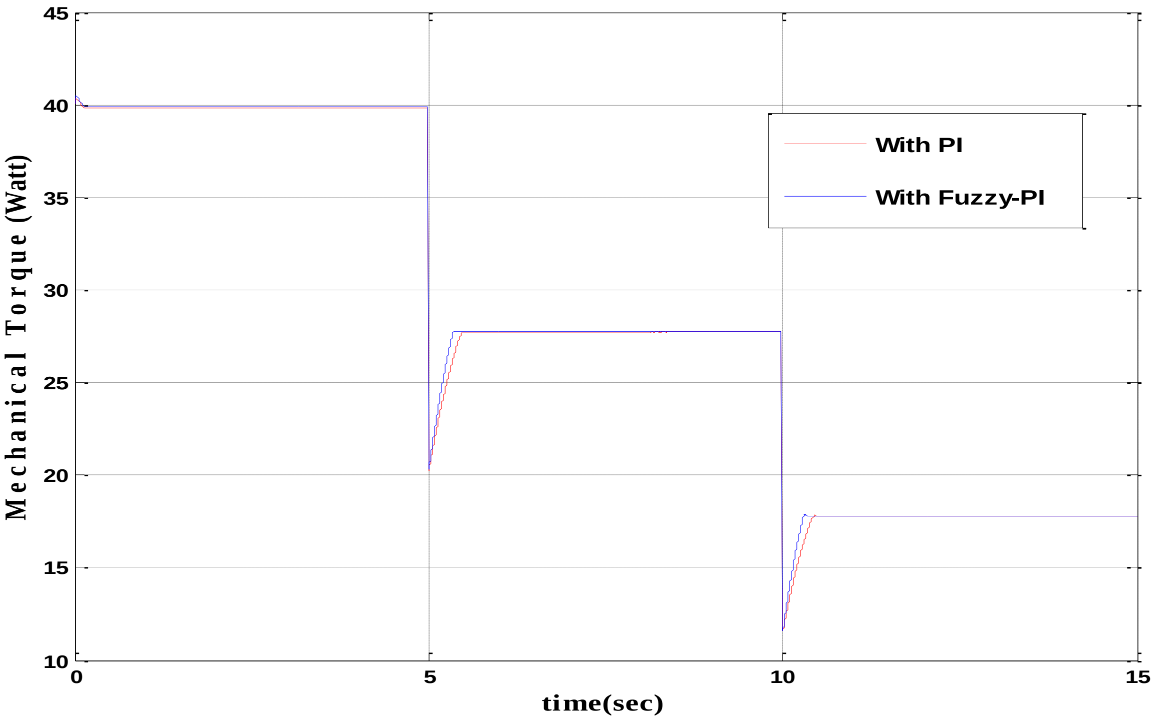

Figure 5.9 Mechanical Torque on the Rotor for Wind Speed Profile Two

Figure 5.10 shows the input voltage from the ac to dc converter in to DC/DC converter. In this figure we can see that there is some oscillation in input voltage due to the snubber capacitance and snubber resistance existed in the rectifier circuit, but it does affect the power extracted from the wind.

.

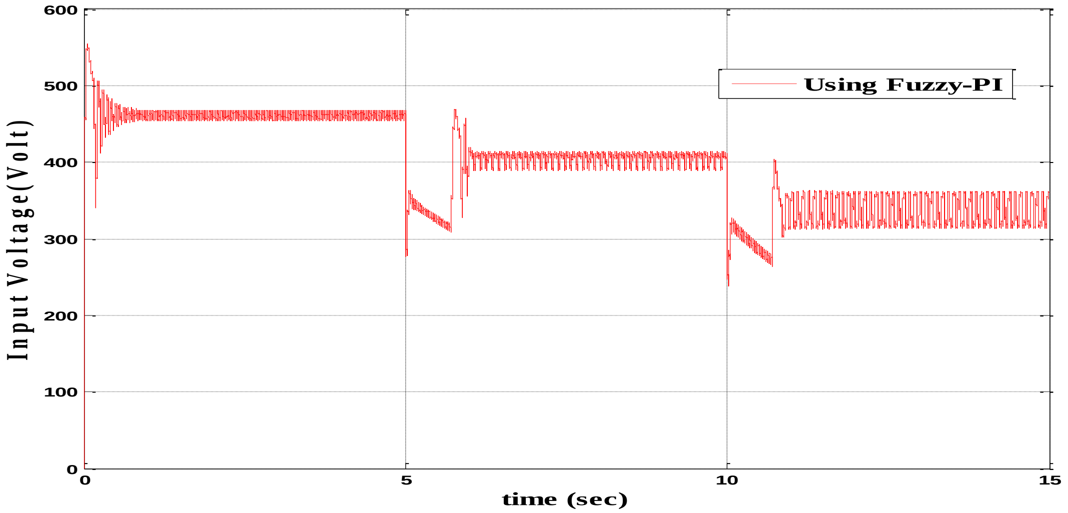

Figure 5.10 Input Voltages to DC/DC Boost Converter

Figure 5.11 shows the output voltage from DC/DC converter. In a boost converter, the output voltage is always higher than the input voltage. From the plots we can see that when the simulation time is between 1sec and 5sec the voltage is step up from 470V to 520V, in between 5sec and 10sec the voltage steps up from 410V to 420V and between 10sec and 15sec it steps up from 355V to 370V. When wind speed changes its pattern, there is delay in both input voltage and output voltage because there is some increment in generator rotor speed. This delay in DC link can be controlled by grid side converter control system that is left as a future work.

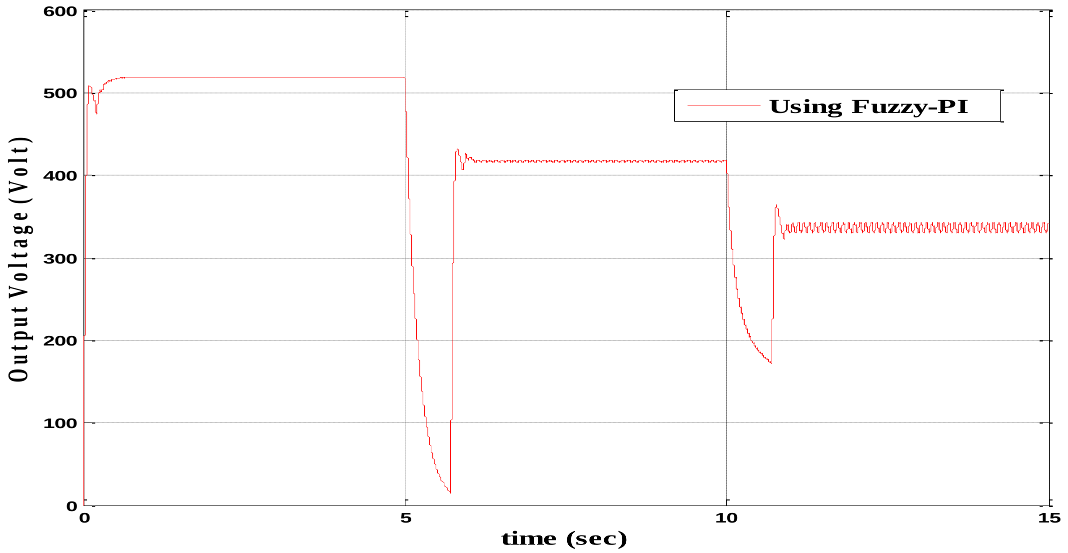

Figure 5.11 Output Voltages from the DC/DC Boost Converter

CHAPTER SIX

CONCLUSIONS AND SUGGESTIONS FOR FUTURE WORK

6.1 RESULTS SUMMARY

Maximum power extraction from wind energy system became an important research topic due to the increase in output energy. This thesis provides a fuzzy logic controller to tune the parameters of PI controller for extracting maximum power from the WECS using permanent magnet synchronous generators (PMSG) via simulation.

Through simulation it has been shown that the proposed control scheme has a great capability of finding the maximum power point of a wind energy system and adapting to wind turbines optimal tip seed ratio under fluctuating wind speed. It can also be observed that the algorithm is successful in controlling the system to mainly operate near its maximum power coefficient value to minimize the loss of potential wind energy.

From the power extracted plots it can be observed that the overshoot given by the self tuning fuzzy PI controller is reduced to 0.09% from 0.2% while the regulation time is reduced to 0.6 s from 1.4s from the PI controller, when the wind speed is 12 m/s (steady state). The overshoot given by the self tuning Fuzzy PI controller is reduced to 0.07% from 0.1% and 0.01% from 0.09% in comparison with the PI controller while the regulation time is reduced to 5.4s from 6.1s and 10.5s from 11.2s from the PI controller, when the wind speed changes suddenly from 12 m/s to 10 m/s and 10m/s to 8m/s respectively. Although the wind power plant is stable with all controllers, a good transient and steady state performance is achieved when we employ a fuzzy self tuning controller.

It is conclude that the maximum power tracking algorithm will be able to efficiently control the wind turbine and capture maximum power output from the wind at any given wind speed below rated wind speed by controlling the rotational speed of the wind turbine.

6.2 FUTURE WORK

Although the maximum power tracking algorithm was proven, by simulation, there are many other studies to be done before this technology can be feasible for industrial application. First, a hardware prototype needs to be constructed in order to implement the controller in real time using a microcontroller. This can be done using a dc motor as the prime mover and controlling the torque of the motor to simulate the torque produced by the wind turbine on the shaft. The motor then can be connected to a permanent magnet synchronous machine, and the electrical system can be implemented.

The second research step that can be taken is to test the maximum power tracking control strategy for bigger generators. As it was shown in appendix A1, the generator used for the simulation was 8.5 kW machine. However, currently utility size wind turbines use generators rated at the megawatts level. A study should be done to analyze the system for machines that have higher inertia.

Finally, besides the maximum power tracking, the maximum power limit control to avoid over rated power excursions due to wind gusts could be done so that a complete power control system is built.

REFERENCES

[1] Ackermann, T., John Wiley & Sons, Chichester, "Wind Power in Power Systems", UK. 2008.

[2] J. F. Manwell, J. G. McGowan, and A. L. Rogers, *Wind Energy Explained: Theory, Design and Application,* West Sussex, England: John Wiley & Sons, 2002

[3] E. Hau, *Wind Turbines: Fundamentals, Technologies, Application, Economics*, 2nd edition. Berlin, Germany: Springer, 2006

[4] [4]R. Y. Redlinger, P. D. Andersen, P. E. Morthorst, *Wind Energy in The 21st Century,* 1stEdition, Palgrave, New York, 2002

[5] N. Surekha, and Dr. K. Ranjith Kumar, "Simulation of Soft Computing based maximum Power point tracking for PMSG Wind Generation System", International Journal of Advanced Technology and Engineering Research, pp. 107-115, 2014.

[6] Ermis, M., Ertan, H. B, "Autonomous Wind Energy Conversion System with a Simple Controller for Maximum-Power Transfer". IEE Proceedings-Electric Power Applications, pp. 421-428. 2009

[7] Wang, Q. e Chang, L."An Intelligent Maximum Power Extraction Algorithm for Inverter Based Variable Speed Wind Turbine Systems". IEEE Transactions on Power Electronics, Vol. 19, pp. 1242-1249. 2002

[8] Q. Wang, L. Chang, "An intelligent maximum power extraction algorithm for inverter-based variable speed wind turbine systems", IEEE Transactions on Power Electronics 19, pg 1242–1249. 2004

[9] M. Chinchilla, S. Arnaltes, J.C. Burgos, "Control of permanent-magnet generators applied to variable-speed wind-energy systems connected to the grid", IEEE Transactions on Energy Conversion, 130–135, March 2006)

[10] L. Whei-Min and H. Chih-Ming, "Intelligent approach to maximum power point tracking control strategy for variable speed wind turbine generation system," vol. 35, no. 6, pp. 2440–2447, 2010

[11] L. Xu and P. Cartwright, "Direct active and reactive power control of PMSG for wind energy generation," IEEE Energy Conversion, vol. 21, Sept. 2008

[12] M Meiqin, Su Jianhui, L Chang, Z Guorong,ZYuzhu "Controller For 1KW-5KW Wind-Solar Hybrid Generation Systems", IEEE Canadian Conference on Electrical and Computer Engineering, pp. 1175-1178, May 2008.

[13] Koutroulis and K. Kalaitzakis, "Design of a maximum power tracking system for wind-energy-conversion applications," IEEE Transactions on Industrial Electronics, vol. 53, April 2006.

[14] H. B. Hendriks, *Application of an advanced cost model in the different design phases of an offshore wind turbine*. Petten: Netherlands Energy Research Foundation, 2001. [onshore offshore]

[15] J. F. Gieras and M. Wing, *Permanent magnet motor technology: design and applications*, 2nd ed. ed. New York: Marcel Dekker, 2002.

[16] J. Pyrhonen, T. Jokinen, and V. Hrabovcova, *Design of rotating electrical machines*. Chichester: John Wiley & Sons, 2008.

[17] M. Yin, G. Y. Li, M. Zhou, and C. Y. Zhao, "Modeling of the wind turbine with a permanent magnet synchronous generator for integration," *2007 IEEE Power Engineering Society General Meeting, Vols 1-10*, pp. 3164-3169, 2007.

[18] S. Morimoto, T. Nakamura, and Y. Takeda, "Power maximization control of variable-speed wind generation system using permanent magnet synchronous generator," *Electrical Engineering in Japan*, vol. 150, pp. 11-19, Jan 30 2005.

[19] F. Iov, M. Ciobotaru and F. Blaabjerg, "Power Electronics Control of Wind Energy in Distributed Power Systems", *11th International Conference on Optimization of Electrical and Electronic Equipment*, Brasov, pp. 867 -884 , May 2008.

[20] L. J. Ontiveros, P. E. Mercado and G. O. Suvire, "A New Model of the Double-Feed Induction Generator Wind Turbine", *2010 IEEE Transmission and Distribution Conference and Exposition*, Latin America, pp. 263-269, November2010.

[21] Boldea and S. A. Nasar, *Vector control of AC drives*. Boca Raton: CRC Press, 1992.

[22] M. Bodson, J. N. Chiasson, R. T. Novotnak, and R. B. Rekowski, "High-Performance Nonlinear Feedback-Control of a Permanent-Magnet Stepper Motor," *First IEEE Conference on Control Applications, Proceedings, Vols 1 and 2*, pp. 510-515, 1992.

[23] G. Moor and H. Beukes, "Power point trackers for wind turbines," Power Elec-tronics Specialist Conference (PESC), pp. 2044–2049, 2004.

[24] H. McLaren, "Neural-network-based sensorless maximum wind energy capture with compensated power coefficient," *IEEE Transactions on Industry Applications,* vol. 41, no. 6, pp. 1548-1556, Nov.-Dec. 2005.

[25] Hilloowala, R. M. e Sharaf, A. M. “A Rule-Based Fuzzy Logic Controller for a PWM Inverter in a Stand Alone Wind Energy Conversion Scheme”. IEEE Transactions on Industry Applications, pp. 57. 2004

[26] R. Esmaili, L. Xu, D.K. Nichols, "A new control method of permanent magnet generator for maximum power tracking in wind turbine application," in *IEEE Power Engineering Society General Meeting*, Vol. 3, pp. 2090-2095, 12-16 June 2005

[27] R. Y. Redlinger, P. D. Andersen, P. E. Morthorst, *Wind Energy in The 21st Century*, 1st Edition, Palgrave, New York, 2002

[28] S. M. Muyeen, J. Tamura, and T. Murata, *Stability Augmentation of a Grid Connected Wind Farm, Green Energy and Technology*, Springer-Verlag, 2009.

[29] Novak, P.,Jovik,I., & Schmidtbauer,B., Modeling and identification of drive- system dynamics inavariable-speed wind turbine. In Proceedings of the third IEEE conference on control applications, Vol.1, 1994.

[30] M.Todorov, I. Dobrev, F. Massouh, Analysis of Torsional Oscillation of the Drive Train in Horizontal-Axis Wind Turbine, ELECTROMOTION 2009 EPE Chapter Electric Drives Joint Symposium, 1-3 July 2009.

[31] I. Boldea, *Synchronous Generators, United States of America*, Taylor and Francis, 2006.

[32] L. M. Fernandes, C. A. Garcia, F. Jurado, “Operating Capability as a PQ/PV node of a Direct-Drive Wind Turbine based on a permanent magnet synchronous generator”, *Renewable Energy*, Vol. 35, pp. 1308-1318, 2010.

[33] Shuhui Li, Timothi A. Haskew, Ling Xu, “Conventional and novel control design for direct driven PMSG wind turbines,” *Journal of Electric Power System research*, Vol. 80, pp. 328-338, March. 2010.

[34] Bose, B. K., *Modern Power Electronics and AC Drives*, Prentice Hall, New York, 2001

[35] M. Vekić, Z. Ivanović, S. Grabić, V. Katić: "Control of Variable Speed Wind Turbine Under Grid Disturbances*", 13th International Symposium on Power Electronics* – Ee 2005, Novi Sad (S&M), Nov. 2005

[36] P. T. Krein, J. Bentsman, R. M. Bass, and B. C. Lesieutre, On the use of averaging for the analysis of power electronic systems," *IEEE Trans. Power Electron.*, vol. 5, no. 2, pp. 182-190, April 1990.

[37] Muyeen, S. M. and Al-Durra, A, "Modeling and control strategies of fuzzy logic controlled inverter system for grid interconnected variable speed wind generator," IEEE System Journal, vol. 7, No. 4, pp 817-824, Dec. 2013.

APPENDICES A: Parameters Used

A1. Wind Turbine Parameters

Parameter	Symbol	Value	Units
Density of Air	ρ	1.225	Kg/m^3
Area Swift by Blades	A_{swift}	1.06	m^2
Optimum Coefficient	K_{opt}	$1.67x10^{-3}$	$Nm/(rad/s)^2$
Rated Wind Speed	V_{rated}	12	m/s
Cut-in Wind Speed	V_{cutin}	4	m/s
Maximum Power Coefficient	C_{p-max}	0.48	-
Optimum Tip Speed Ratio	λ_{opt}	8.1	-
Nominal Mechanical Output power	$P_{nominal}$	8.5	KW

A2. Electrical Machine Parameters

Parameter	Symbol	Value	Units
No. of pole pairs	P	5	Kg/m^3
Rated Speed	ω_r	152.89	rad/sec
Rated Current	I_{rated}	12	A
Armature Resistance	Rs	0.425	Ω
Stator Inductance	L_d, L_q	0.0082	mH
Rated Torque	τ_{rated}	40	Watt
Rated Power	P_{rated}	6	KW
Flux induced by magnets	ψ	0.433	Wb
Moment of Inertia	J	0.01197	$Kg.m^2$

A3. The DC-To-DC Boost Converter Parameters

The dc-to-dc converter parameters were obtained by selecting a power rating based on the generated power capacity and voltage ripple requirements for the output voltage of the converter. The equations used to obtain these values were given in chapter 3, section 3.4.2.

The parameters are shown in table below.

Parameter	Symbol	Value	Units
Low voltage side capacitor	C_1	500	μF
High voltage side capacitor	C_2	3600	μF
Inductor	L	200	μH
Switching frequency	f_{dc}	20,000	Hz
Load Resistance	R_L	35	Ω
Duty Cycle	D	0.598	-