Simulation of Wind Turbine Emulator

Using DC Motor

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CERTIFICATE

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ABSTRACT

Global warming and increasing oil prices has led the world to discover new energy resources which are environment friendly and are found in abundance so that they never go out of stock. Wind energy is one of the forms of renewable source of energy which can be used to generate electrical energy. In wind technology, a wind turbine is used to convert the kinetic energy of the wind into mechanical energy which is connected to a generator with or without a gearbox to produce electricity. A generator is used to convert the mechanical energy coming out of turbine rotor into electrical energy and this energy can be used in standalone systems or connected to the grid. This whole system from i.e. wind turbine to grid is known as wind energy conversion system.

Wind turbines are large in size and are mounted on a tower at a height, so study of wind turbines is a troublesome and unpleasant issue. Moreover, wind is also arbitrary in nature and hence wind speeds change constantly with time. So to study wind turbine and see the performance of wind turbines on different conditions of wind speeds and pitch angle, a turbine model is created in Matlab environment which is run through a motor giving the same characteristics of turbine and the name given to such configuration is wind turbine emulator.

In this thesis, wind turbine emulator is designed using a separately excited direct current motor operating with a chopper circuit where error control is achieved through a proportional integral controller. This wind turbine emulator is then directly connected to permanent magnet synchronous generator to check if the generator could build up the required rated voltage on a specified load.

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LIST of SYMBOLS and ABBREVIATIONS

ω = speed of turbine in radian per second

R = rotor radius in metres

V_w = wind speed in meter per second

C_p = coefficient of power or coefficient of performance

m = mass of air in kilogram

ρ = air density (1.225 kg/m^3)

λ = tip speed ratio

P = number of poles

Z = Total number of conductor

A = number of parallel paths

Φ = flux per pole in Weber

ω_m = speed of motor in radians per second

e_b = total induced back EMF

K_b = EMF constant

v_a = applied dc voltage on motor

R_a = armature resistance in ohm

L_a = armature inductance in Henry

i_a = armature current in ampere

J = inertia of motor in kg/m^2

B = Friction constant

R_s = resistance of stator winding

ω_e = generator electrical rotational speed

v_{sd} , v_{sq} = d and q-component of instant stator voltage

i_{sd} , i_{sq} = d and q-component of instant stator current

ψ_{sd} , ψ_{sq} = d and q-component of instant stator flux

L_{ls} = stator winding leakage inductance

L_{dm} , L_{qm} = stator and rotor d and q-axis mutual inductances respectively.

ψ_f = permanent magnet produced flux linkage

$v_{a(max)}$ = maximum input voltage

v_o = desired output voltage

η = efficiency of converter

D = Maximum Duty Cycle

f_s = minimum switching frequency of converter

ΔI_L = inductor ripple current

i_f = average forward current of diode

v_f = forward voltage of diode

e(t) = error signal

K_P =Proportional control gain
K_I = Integral control gain

V_r = peak value of reference signal

M = modulation index

V_{cr} = sawtooth carrier signal

WECS = Wind Energy Conversion System

PMSG = Permanent magnet synchronous Generator

WRIG = Wound Rotor Induction Generator

SCIG = Squirrel Cage Induction Generator

DFIG = Doubly Fed Induction Generator

PWM = Pulse Width Modulation

PI = Proportional Integral

EMF = Electro Motive Force

DC = Direct Current

HAWT = Horizontal Axis Wind Turbines

VAWT = Vertical Axis Wind Turbines

TSR = Tip Speed Ratio

CHAPTER-I

INTRODUCTION

1.1 GENERAL

The burning topic in today's world is pollution and global warming as greenhouse gas emissions are increasing day by day in atmosphere due to persistent use of fossil fuels. The main long term effects include global temperature increase and rise in sea water level due to melting of polar ice caps. Warnings are issued by climate scientists about the potential catastrophic effects with the use of fossil fuels [3]. Countries have given priority to the use of fossil fuels so as to power their economies and that has accelerated the amount of carbon dioxide into the atmosphere which is regarded as the main cause of climate change. Thus the need of the hour is to shift energy generation techniques from non-renewable to renewable which is pollution less and eco friendly form of energy. Renewable sources of energy are eco friendly and will never run out of stock as these sources are unlimited unlike fossil fuels which may end in next 50-60 years.

Environmental friendly and economically reusable source of energy which can be tapped effectively using generators is wind energy. In the last two decades the total power generated through wind systems has increased substantially, with advancement in technology that is new advanced power electronics converters, optimal power tracking and better system integration, and hence cheap and good quality of energy can be produced effectively [39].

Wind turbine technology provides cost effective solution to end the dependence on very costly oil and gas which is now used to generate electricity [2]. Also, wind technology provides energy without greenhouse effect or deadly pollution release. If we compare the installing and generating costs of wind turbine technology with conventional generating schemes such as coal fired steam alternators, geothermal, hydrothermal and nuclear reactor based generator, we find that it is lower than conventional schemes. It gives a cost effective alternate source of renewable energy. A wind turbine makes use of wind energy to produce electricity whereas a fan needs electricity to produce wind. To describe it in a more sophisticated manner, the kinetic energy of wind is converted into electrical energy by a wind turbine. These wind turbines comes in different shapes and sizes depending on rotor used and power generating capacity. Small wind turbines having capacity below 10 kW are mainly used in irrigation water pumping, telecommunication dishes and at residences. Large wind turbines having higher power rating that is from 100 kW to 5 MW are also known as utility scale wind turbines.

In the last two decades the world has shifted towards the utilization of renewable energy sources. The global estimated wind capacity is 432 GW at the end of 2015 with India being the 4th largest harnesser with 26 GW productions [1]. Compared to non-renewable fossil fuels wind energy is clean and green so wind energy generation has become a big contributor and hence encouraging wind based research. Since it is pretty troublesome to work on a real wind turbine so a laboratory model is designed using DC motor for purpose of studying the behaviour of wind turbine. On a wind emulator the pitch angle or wind speed can be changed and the corresponding change in characteristics and behaviour of a wind turbine is determined which is otherwise not possible with a real wind turbine as wind speed is arbitrary in nature. Wind turbine emulators have evolved as a tool to study the power conversion process and to increase the quality of power of a wind energy conversion system [36]. The structure of a wind turbine emulator scheme is shown in the figure1.1 which is designed in a MATLAB\SIMULINK environment.

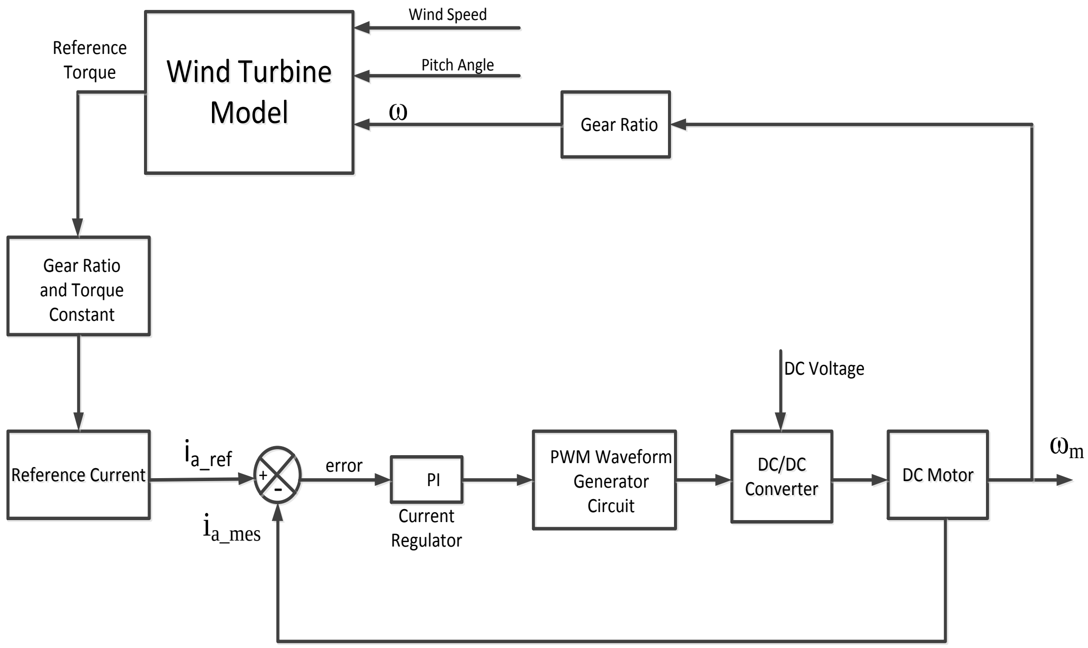

Figure 1.1 Structure of a Wind Turbine Emulator Scheme (WTES)

Winds are caused because of surface irregularities of earth, rotation of earth and non uniform heating of atmosphere by the sun. Generating energy from wind has many advantages such as it delivers efficient and environmentally friendly electrical energy at low cost particularly in remote locations [3]. Wind energy technology provides off-grid living and home-made electrical energy that is not possible with conventional technologies. The property that makes wind reliable and depends upon is the abundance of availability of wind and thus it is sustainable. The installation of wind mills does not affect the value of commercial building or home. Even if the installations are undone, there is no adverse effect on installation sites. Wind turbines don't require frequent maintenance or employment to operational personnel. Unlike gas and steam turbine systems, no operational or maintenance costs are incurred.

1.2 OBJECTIVE OF THE PRESENT WORK

At the end of this project work the following objectives are attained:

1. Study classification and structure of wind energy conversion system. Types of generators and power converters used in different schemes in wind energy conversion system.
2. Study the type of wind turbines, their workings and area of use. Analysis of some of the performance parameters associated with wind turbines.
3. Analysis and mathematical modelling of wind turbines. Study of different control schemes used for wind turbines in wind energy conversion system.
4. From the modelled wind turbines get power-speed and torque-speed characteristics to study the behaviour of wind turbines.
5. Calculation of the values of converter parameters that is buck converter parameters.
6. Comparing and controlling the dc motor model to get wind turbine characteristics so that dc motor can emulate the wind turbine in small scale applications. Study operation of wind turbine emulator driven permanent magnet synchronous generator for electricity generation.

1.3 ORGANIZATION OF THE THESIS

Chapter 1 describes the introduction of the project. It describes why the wind technology is chosen as the research work and also how the world is shifting towards the use of wind energy instead of conventional fossil fuels. It also describes the research perspective i.e. why this field of research work is chosen. This chapter also provides the organization of the report.

Chapter 2 elaborates the literature review used in the present work. It first discusses paper and books on wind energy conversion system and wind turbines. Then it discusses papers on converter and controlling technique used in research work and lastly it analyses papers on wind turbine emulator using dc machine. Conclusion of entire literature review is given at the end of this chapter.

Chapter 3 describes about the wind energy conversion system, the wind turbines, their types and uses in different operations. It defines the associated terms used in wind energy systems. It also gives information about the wind simulators and characteristic curves of wind turbines i.e. turbine power versus turbine speed curve and turbine torque versus turbine speed curve. These characteristic curves are to be emulated using a dc machine.

Chapter 4 discusses about the dc machine speed control and parameters taken into the simulation and the calculations done to get the parameters of buck converter. It provides information about the controller used i.e. the PI controller. This chapter also describes about the armature control regulation of dc motor using PI control and pulse width modulation controller.

Chapter 5 presents the characteristics of wind turbine which are to be emulated using a dc motor. A mathematical model on the operation characteristics of wind turbine is made using its power and torque equations. It tells how the controlling of dc motor is done so that the required characteristics are obtained. C_p versus λ curves, power versus speed and torque versus speed curves are obtained. A variable wind speed profile is created and according to that wind profile parameters like motor speed, power coefficient, tip speed ratio, reference armature current and actual armature current are studied. Integration of wind turbine emulator with a permanent magnet synchronous generator is done so as to see if the system designed is able to generate required voltage and current when a fixed load is given at PMSG terminals.

Chapter 6 presents main conclusion and future scope of the research work.

CHAPTER - 2

LITERATURE REVIEW

2.1 GENERAL

Global warming is a very important issue for the world as the temperature of earth is increasing day by day mainly due to use of fossil fuels. The human activity which leads to green house effect includes thermal power plant, forest fire, combustion of fossil fuels, emissions from traffic etc. The harmful effects of global warming include soil moisture imbalance, loss of biodiversity, melting of glaciers etc. So the dire need of hour is to shift our energy generating techniques from non renewable to renewable sources of energy.

Wind energy is eco-friendly source of energy which can be used instead of oil and fossil fuels. The installing and generating cost of wind turbine technology is lower as compared to conventional energy generating schemes. It is not easy to work on a real wind turbine so a MATLAB/SIMULINK model is created and on that model pitch angle of blades is changed on different wind speeds to see the turbine behaviour which is not possible on a real wind turbine as wind speed is arbitrary in nature. Wind turbine emulator is realised using a separately excited dc motor in MATLAB/SIMULINK environment and this chapter provides literature review on wind energy conversion system, controlling techniques and wind turbine emulator using dc motor.

2.2 WIND ENERGY CONVERSION SYSTEM

The increase in the prices of fossil fuels in 1970 led the attention of the world to shift from non-renewable to renewable sources of energy like wind and solar energy [5]. Windmills have been in use for more than a thousand years and their clear evidence have been found in Middle East and Afghanistan. If a man works very hard all day, he can do 1 kWh of useful work and conventional windmills provided work of about hundred men or a dozen horses i.e. why it survived for so many centuries. By the end of 18th century Netherlands and Britain had about ten thousand windmills. James Smeaton and Golding gave synopsis on major work in the development of windmills in their respective books [6].

John Twidell [7] et al. in their article discussed about the considerations that must be taken about the complete system which includes turbines, generators, controllers and end users to fully use wind power. Such an arrangement may be known as small wind energy conversion system. Wind turbines can be classified on their scale. Small machines may be categorised into ‘mini’ and ’standard’ machines. Mini scale machines are used for lightening, telecommunication and small power tools i.e. for single household purpose. Standard sized machine are used to supply heat and electricity to utility grids for purpose of sale. Standard sized machines are used on farms and industrial premises. Careful design is needed for wind turbines and towers as the main problem is of fatigue and harsh environment. In thirty years a small machine may experience 10^{10} fundamental stress, so careful monitoring and maintenance is required with these small machines. In batteries energy is stored in the form of dc power. Mini systems are used with dc generation and rectification is used with ac generation. Induction generators are used which are excited from grid linked machines. The benefit of this is that the generator ceases to generate in case of grid failure ensuring safety of line. The scale operation favours electronic control which is cheap and rigid.

In [8] F.M.H. Khater has explained different power electronic techniques used in wind energy conversion system. Converters convert generated power from one form to another form and this controls the operation of system. Selection of converter is very important aspect for generator type, control purpose and output form. In [9] T. Jiang et al. have described identification of wind energy conversion system by using prediction error method algorithm. Two theoretical models are taken in two different situations, linearized around operating point and state equations are built to compare both the models and their differences are analysed in detail. Z.Chen [10] et al. investigated the performance of power system when a disturbance occurs in the system like sag caused by a short circuit. It showed that continued transfer of real power, achieved from the wind, is realised using a voltage source converter.

A.C. Hua [11] et al. proposed design scheme and implementation of power converters for wind energy systems which included a system with a permanent magnet synchronous generator, a boost converter with a full bridge inverter. A digital signal processor is used as system controller to keep producing maximum power from generator. Mahmoud M.N. Amin [12] described how the power quality can be improved in wind system with a synchronous generator. An uncontrolled rectifier digitally controlled inverter system is proposed which is simple as the number of controlled switches is less which makes it less complex. In paper [13] S. Fan et al. described the control and design of series parallel current output resonant converters. Resonant converters have the benefits of both series resonant converters and parallel resonant converters. These converters are used to interface multiple wind turbines with multi terminal dc micro grid. In paper [14] Ruchika et al. used a permanent magnet synchronous generator to connect with wind energy conversion system taking battery as energy storage device for an isolated load so that the mismatching of load can be prevented and energy could be stored without difficulty.

H. Ahuja [15] et al. analysed permanent magnet synchronous generator based wind energy conversion system relating to power quality, wind speed range and balance of power under changing wind speeds. A. Dhabi [16] studied the performance of permanent magnet synchronous generator with wind energy conversion system. Wind Turbine usually operates at different speeds, therefore in order to extract high power from decoupling generator and wind, some popular rectifiers are used like active six-switch two level rectifier, DC-DC converters etc. Their performances are examined and results are being compared. In paper [17] R.A. Gupta et al. compared the variable speed wind turbine and constant speed wind turbine on two parameters, first one is power fluctuations and second one is reactive power supply.

2.3 WIND TURBINE EMULATOR

In [18] L. Chang et al. have designed a wind turbine simulator which implements a real wind turbine controller. In this paper the induction motor used is of 125 hp rating which is connected to a low speed generator. The motor is driven by a control software and variable speed drive inverter. In [19] M. Chinchilla presented a lab setup which could be used as wind turbine emulator which can be used as a tool to study the operation, control and behaviour of a wind turbine. A dc drive is used to reproduce the actual turbine torque. Wind velocities are read from a file by a control program and a reference torque is created which is given to the dc drive. Stall and pitch controlled wind turbines can be emulated by using this scheme in the laboratory. Oscillating and mean torque is emulated and hence its functionality can be checked in power quality. L.A. Lopes [20] et al. have build a laboratory prototype of a wind turbine with a permanent magnet dc motor driven either by a three phase rectifier or a pulse width modulated dc/dc converter. Results shows the internal limitations of thyristor rectifier and these problems are removed by dc/dc converter.

In [21] F.J. Lin et al. have proposed intelligent control of wind emulator with induction generator using Radial Basis Function Network (RBFN). Closed loop emulator is made to give maximum power for induction generator at different win speeds using RBFN. M. Arifujjaman [22] et al. have proposed an emulator in which a dc motor is coupled to a synchronous generator where dc motor is controlled by a PC. Wind speed and rotor speed information is used by a dynamic controller which controls the duty cycle of converter so that the wind turbine operates at optimum tip speed ratio. In [23] Weiwei Li et al. have implemented a DSP based wind turbine emulator using a separately excited dc motor. To get real time control, interfacing is done using a PC in C language.

R. Ovando [24] et al. have designed a wind emulator using a dc motor. DC motor is coupled with doubly fed induction machine which actuates as a generator in a wind energy conversion system. Weihao hu [25] et al. have designed and implemented a wind emulator using permanent magnet synchronous motor. The test bench includes an intelligent power module inverter, microcontroller, permanent magnet synchronous motor and a control desk. By controlling the frequency and stator current the output torque of motor can be regulated. In [26] Fernando Martinez et al. emulator consists of a resistance, dc motor and a dc voltage source all in series with each other. In [27] S.W. Mohod et al. proposed work to design variable speed wind energy conversion system under variable wind speed and to realise this induction motor drive using scalar control is interfaced with the system. Volt/ hertz speed control scheme is used for induction motor and d-SPACE provides the power curve to wind generator.

K. Ohyama [28] et al. proposed blade element momentum theory to design a wind turbine emulator. Using fluid analysis lift coefficient and drag coefficient are calculated for used blade shape in the paper. Different wind speeds at different height and tower shadow effect are considered and emulator behaves satisfactorily. In paper [29] Hsiang-Chun Lu et al. designs a wind turbine emulator and evaluates how emulator is used to help in enhancing the performance of wind energy conversion system. [30] Santaphon Kumsup et al. developed wind emulator consisting of real time interface card, induction motor and torque inverter. The test in laboratory was done on 1 kW separately excited dc generator. Manual or programmed wind speeds are used and the power and torque response of emulator was satisfactory. In paper [31] J. Vaheeshan et al. developed wind turbine emulator using a dc motor and verified it through Matlab simulation. The torque output at the wind turbine model is made to be generated at the dc motor shaft. The paper depicts turbine power control strategy which takes into account effects of load components with shaft dynamics.

In paper [32] Trevor Hardy et al. modelled a 1.5 MW wind turbine model using the available data. By relating this data, a function is made for maximum output power and wind velocity along with turbine's one mass model. The simulation was run in Lab-VIEW software and data is read from a file which contains optimal power from wind velocity, wind velocity data and control signals for dc motor. Actual power generated by dc motor and power calculated from simulation is compared by taking mean square error so that effectiveness of the system could be understood. A. Mahdy [33] et al. emulated the characteristics of a small wind turbine by taking a armature controlled separately excited dc motor which is driven by a thristor dc drive cascaded with a closed loop PI controller. A small analog electronic circuit is designed which generates a reference speed for rotor taking into account wind turbine characteristics at a certain wind speed. M. Liu [34] et al. made a mathematical model of a wind turbine and intimated its characteristics using a dc motor. Imitation is done by using closed loop current control of dc motor and results are consistent with the theoretical data. In paper [35] Lei Lu et al. designed a dynamic wind turbine emulator as it has taken tower shadow and wind shear into account. The induction motor is driven by a inverter and reference is taken by dynamic torque which controls the induction motor. This model is working very close to an actual wind turbine and could be used as replacement for actual wind turbine in case of lab experiments. S.K. Bagh [36] et al. emulated characteristics of a horizontal axis wind turbine using a dc motor which if further driving a permanent magnet synchronous generator for generation of power. Dynamics of turbine generator set inertia and tower shadow effect causing three pulse oscillations are considered and implemented in this paper. The dc link voltage is maintained at 1 kV through generator side control which provides constant electrical load for emulator i.e. the prime mover.

In paper [37] S. Kouadria et al. developed a wind turbine emulator circuit using separately excited dc motor, controlled by buck converter and a real time interface card i.e. d-SPACE. Controlling of dc motor is done through proportional integral regulator. S. Kouadria [38] et al. compared reference current from turbine to actual armature current of motor and the error is provided to the hysteresis current regulator which provides the gate pulses to buck converter which controls the operation of dc machine according to the duty cycle. In paper [39] Filipe Emanuel Vieira Taveiros et al. developed a wind emulator and investigated the acceptability of thyristor three phase six pulses for wind energy conversion system. In paper

[40] Syed Naime Mohammad et al. presented recent developments and trends in wind energy conversion system with different generators and their respective technical challenges, different topologies of converters, their classification, generator choice and their benefits. M.A. Bhayo [41] et al. modelled and designed wind turbine emulator based on a dc machine. PI controller is used so that dc machine exactly follows rotational speed of turbine rotor. In paper [42] Richa V et al. real time digital simulator is used to develop a fixed speed wind turbine emulator. This model of wind turbine is made in RSCAD software environment. Using perturbation methods and a auto-regressive moving average method the software model generates required torque signals. These signals are given to a servo motor which emulates a wind turbine and were provided to induction machine behaving as generator.

2.4 CONCLUSION

Emulation of wind turbine characteristics can be done using different motors like dc motor, synchronous motor, induction motor or servo motor. Most of the papers use dc machine to emulate wind turbine characteristics because speed control is easy in dc machine as compared to ac machines.

CHAPTER-III

WIND ENERGY SYSTEMS

3.1 WIND ENERGY

The components of a wind energy conversion system include a rotor turbine, a gear box,a generator, a power electronic system and a transformer for connecting to grid [43]. Firstly, power from wind is captured through wind turbine blades which convert wind into mechanical power. When the wind speed is high, it is very important to control and limit the mechanical power. The easiest and most common way to convert the low speed and high torque mechanical power into electrical power is by using a gear box and generator. Gearbox is used so that the high speed of generator could be adapted with low speed of turbine rotor. Generator is used to convert the mechanical power into electrical power which is then fed into the grid may be through a transformer with electricity meter and circuit breakers. Figure 3.1 shows the block diagram of wind energy conversion system (WECS).

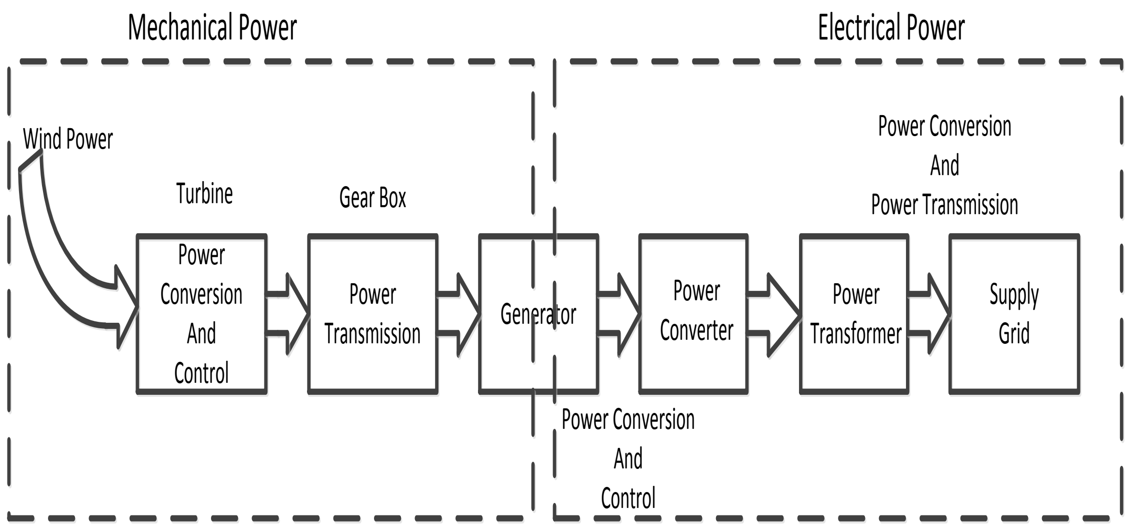

Figure 3.1 Block Diagram of Wind Energy Conversion System

3.1.1 Wind Generators

The generator used in wind extraction system could be induction type or synchronous generators. Fixed speed wind turbines use induction generator with cage rotor due to damping effect. Parallel capacitors or network should provide the reactive power necessary to energise the magnetic circuit [43]. Voltage instability problem may be faced as the terminal voltage or reactive power is not directly controlled. A wound rotor induction machine can be connected to external resistor or ac system with the use of power electronics. This may provide partial variable speed operation for higher energy yield at wind speeds lower than rated speed. In case of synchronous generators, they are excited either by permanent magnets or by external dc. Synchronous generators are not directly connected to grid due to requirement of high damping in drive train. To decouple the generator from the network full rated power electronic conversion system is used.

3.1.1.1 Grid Connected Generators

A) Squirrel Cage Induction Generator (SCIG): it can be connected directly to the grid via a transformer and SCIGs operate at nearly constant speed. The main advantage is cheap and simple construction but its disadvantage includes operation at constant speed and for stable operation stiff power grid is required [43]. But when an induction generator is connected with a power system, very high inrush currents of short duration are caused which makes disturbance in grid as well as in drive train. A thristor soft starter is generally used to limit the high starting currents.

B) Wound Rotor Induction Generator (WRIG): rotor resistance control is achieved in this case by connecting the rotor windings with variable resistors. In this method as the rotor winding resistance goes high the slip also increases. This system is used for variable speed operation. To generate electricity both the generators i.e. SCIG and rotor resistance controlled WRIG needs to operate above synchronous speed, so both will draw reactive power which is supplied by capacitor banks or by the grid. Power converters are necessary to connect WRIG with the grid.

C) Doubly Fed Induction Generator (DFIG): the rotor of DFIG is connected to grid via full scale power electronic converters by slip rings and stator is directly connected to grid. This system is used in variable speed operation and the generator can provide energy to grid at both sub-synchronous and super-synchronous speeds [43]. The advantage of this system is that only a part of power produced is fed through power converter so the nominal power rating of power converter is less than nominal power rating of turbine.

D) Synchronous Generator: these generators are excited by externally applied dc. Synchronous generators are connected to grid via full scale power converters because they require significant damping in the drive train [40]. They are used in variable speed operation of wind turbines.

E) Permanent Magnet Synchronous Generators (PMSG): the advantages of PMSG are low loss, smaller size, high efficiency, self excitation and higher power factor. Rotor flux is produced by permanent magnet so no magnetizing current is required and hence torque is produced by stator current [43]. Due to permanent magnet there are no copper losses in a PMSG and hence it operates at a higher power factor and higher efficiency. These are also used with variable speed operations and hence power converters are necessary to connect it with a grid.

3.1.1.2 Isolated Wind Generators

In applications like pumping of water for agricultural use, electricity for rural community at a remote place and petroleum refining at off-shore location, isolated wind generators are used. Asynchronous generators compared to synchronous generators are preferred in case of isolated wind generators with some energy storage system because asynchronous generators are proved less complex in terms of control.

3.1.2 Power Converters

Power converters in last 25 years have changed completely and its use has increased in number of applications. The performance is increasing day by day and at the same time prices are falling. Advancements in power electronic devices like insulated gate bipolar transistor (IGBT), MOSFET, MOS gate thyristors, integrated gate commuted thyristor (IGCT), and silicon carbide FETs has enhanced the efficiency of converters. Power electronic devices are used for protection, driving and control mechanism which is necessary for voltage variation or frequency control in WECS. Depending upon the applications and topology of a converter, it may allow flow of power in both directions.

3.1.2.1 Wind Turbine Systems with Full Scale Power Converters

A) Grid Connected Induction Generator with Gearbox

Figure 3.2 gives the integration of induction generator with the grid [43]. Full scale power converters usually of back to back voltage source converter are used for achieving active and reactive power control.

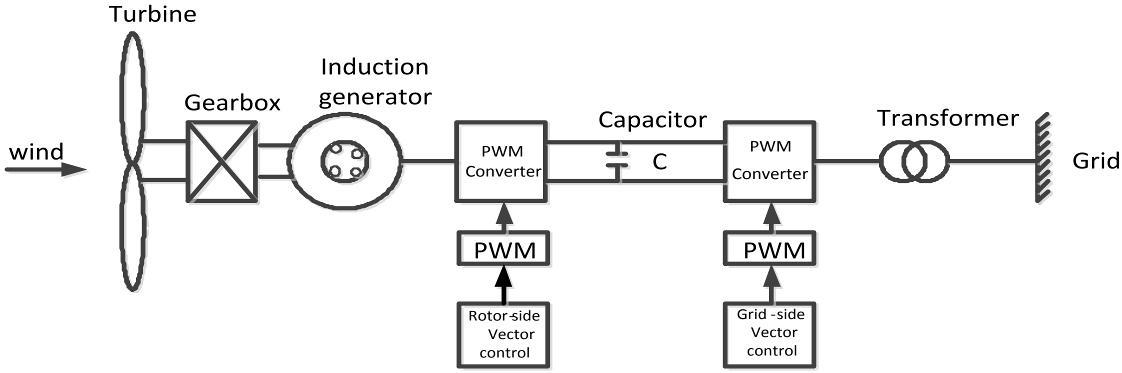

Figure 3.2 Grid Connected Induction Generator with Gearbox

B) Grid Connected Synchronous Generator with Gearbox

Figure 3.3 shows integration of synchronous generator with the grid. Gear box is used when connecting synchronous generator with wind turbine so that the low speed of turbine can be matched with high speed of generator [43]. Diode rectifiers may be used with synchronous generator but with the drawback that it would be difficult to fully control the whole system. For field excitation a small power converter may be required.

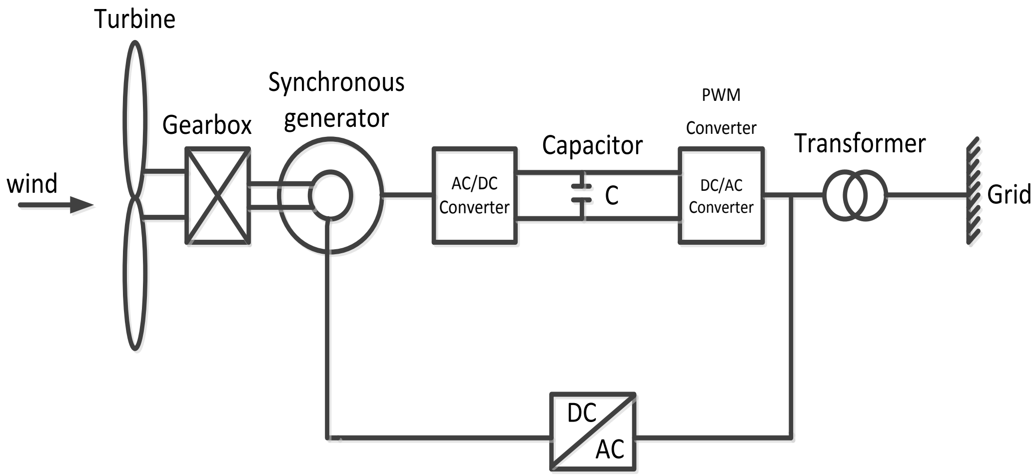

Figure 3.3 Grid Connected Synchronous Generator with Gearbox

C) Grid Connected Multi-pole Synchronous Generator

In case of multi-pole synchronous generator gearbox is not needed and figure 3.4 shows the scheme of the system.

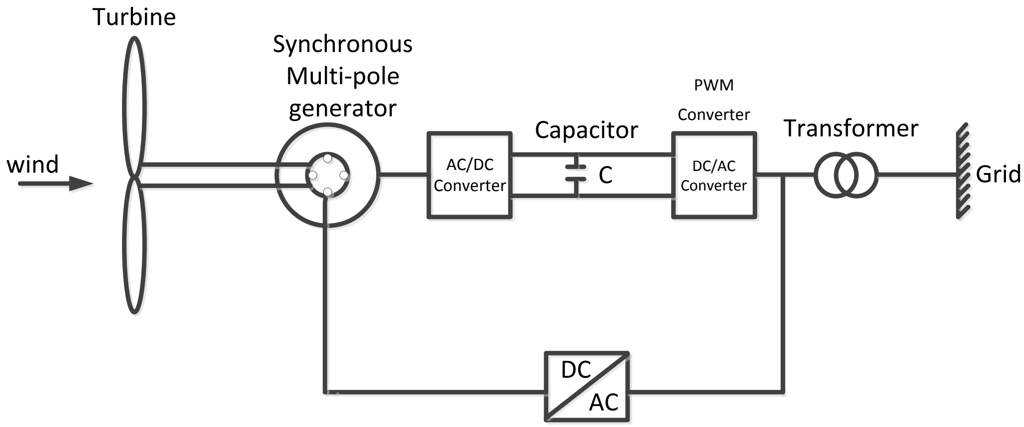

Figure 3.4 Grid Connected Multi-pole Synchronous Generator

D) Grid Connected Multi-pole PM Synchronous Generator

In multi-pole permanent magnet synchronous generator, gearbox is not required and these are becoming popular nowadays because they are cheaper and reliable [43].

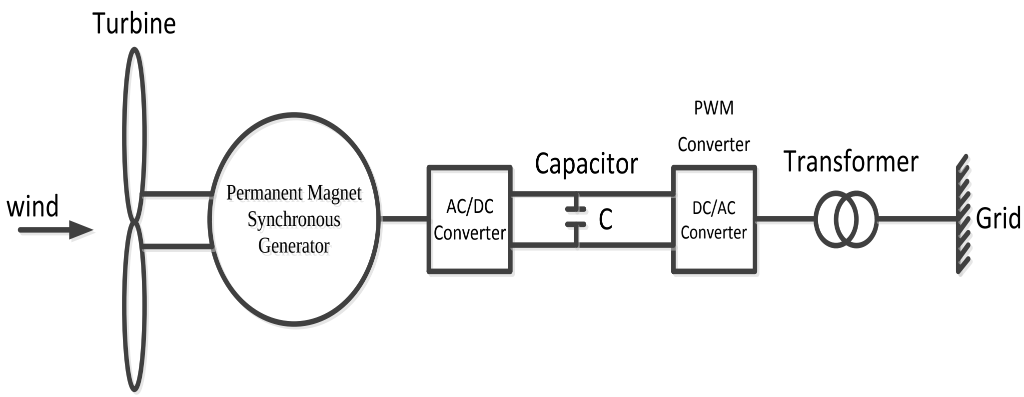

Figure 3.5 Grid Connected Multi-pole PM Synchronous Generator

3.1.3 Classification of WECS

Wind energy Conversion system is classified on different parameters such as rotor speed, power control and power utilization [2]. Figure 3.6 shows the classification of WECS.

3.1.3.1 Rotor Speed Parameter Concept

It is of two types i.e. variable speed and constant speed. In case of constant speed concept, the wind turbine rotor speed is constant i.e. it does not depend on load conditions. The power which is to be produced by a wind turbine is determined by wind speed. In case of variable speed concept, maximum power or close to maximum power is obtained by wind turbine as rotor speed changes with change in wind speed.

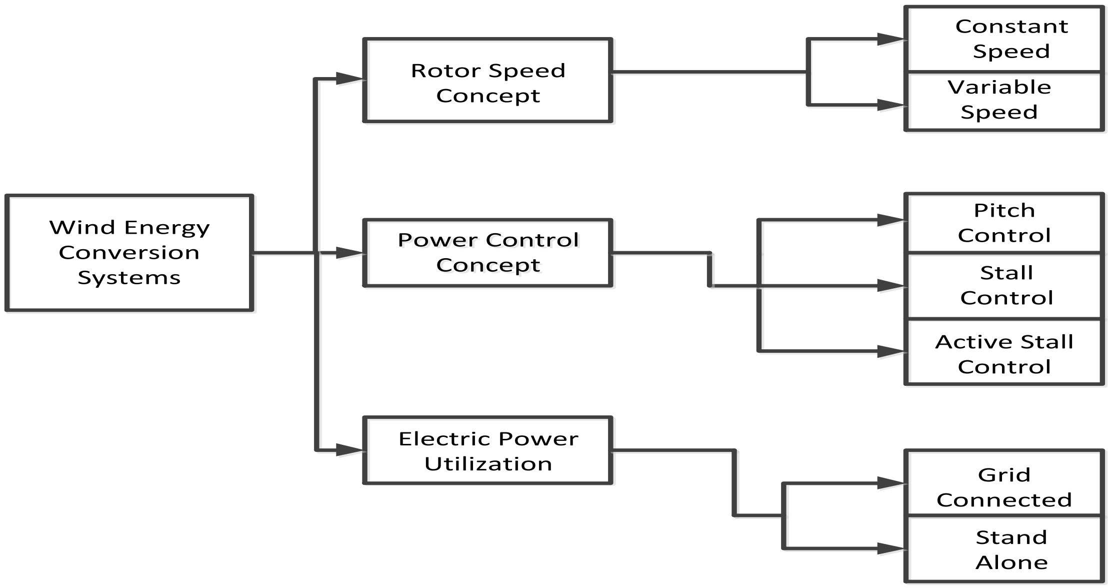

Figure 3.6 Classification of Wind Energy Conversion System

3.1.3.2 Power Control Concept

The three sub-categories of this case are stall control, pitch control and active stall control. In case of passive stall control, the blades of turbine are so designed that wind speed above a certain limit will cause less power capture and wind speeds above another limit will cause the blades to stall i.e. no power will be captured. In pitch control, the blades are turned into or out of the wind (pitching of blades) to control the power capture. In active stall control, above mentioned both passive stall control and pitching control is used in design of rotor.

3.1.3.3 Electric Power Utilization

This type is characterized by stand alone or grid connected configuration. Different generators are used in different configuration in grid connected WECS. SCIG is used in constant speed configuration and WRIG is used in variable speed configuration. A series resistor is there with rotor winding which controls the slip of generator. In case of doubly fed induction generator the rotor reactive power is controlled to control the speed. In case of stand-alone systems power may or may not be available all the time so it has to be backed up with some energy storage system. They are mainly used in pumping water, residential heating or desalination of sea water.

3.2 WIND TURBINES

A wind turbine makes use of wind energy to produce electricity whereas a fan needs electricity to produce wind. To describe it in a more sophisticated manner, the kinetic energy of wind is converted into electrical energy by a wind turbine. These wind turbines comes in different shapes and sizes depending on rotor used and power generating capacity. Small wind turbines having capacity below 10 kW are mainly used in irrigation water pumping, telecommunication dishes and at residences. Large wind turbines having higher power rating that is from 100 kW to 5 MW are also known as utility scale wind turbines. In the last two decades the world has shifted towards the utilization of renewable energy sources. The global estimated wind capacity is 432 GW at the end of 2015 with India being the 4^{th} largest harnesser with 26 GW productions [1]. Compared to non-renewable fossil fuels wind energy is clean and green so wind energy generation has become a big contributor and hence encouraging wind based research.

It would be troublesome to work on a real wind turbine for research work so a same replica is designed [19]. The torque-speed and power-speed characteristics of wind turbine are created through an electrical machine in a MATLAB-SIMULINK environment. Wind turbine captures the wind energy so it becomes important to study the characteristics of a wind turbine. There are mainly two types of wind turbines which depend on orientation of axis of rotation [3].

- Horizontal axis wind turbines (HAWT)
- Vertical axis wind turbines (VAWT)

3.2.1 Horizontal Axis Wind Turbines

In horizontal axis wind turbines, the electrical generator and rotor are kept at topmost of tower facing the wind [3]. In this design, power output and rotor speed can be effectively controlled on longitudinal axis by pitching the rotor blades known as blade pitch control. In case of over-speed or high wind speeds, the most effective method is blade pitch control mainly in large wind turbines. Aero-dynamical optimization of rotor blade shape is made to reach maximum efficiency in case of HAWT.

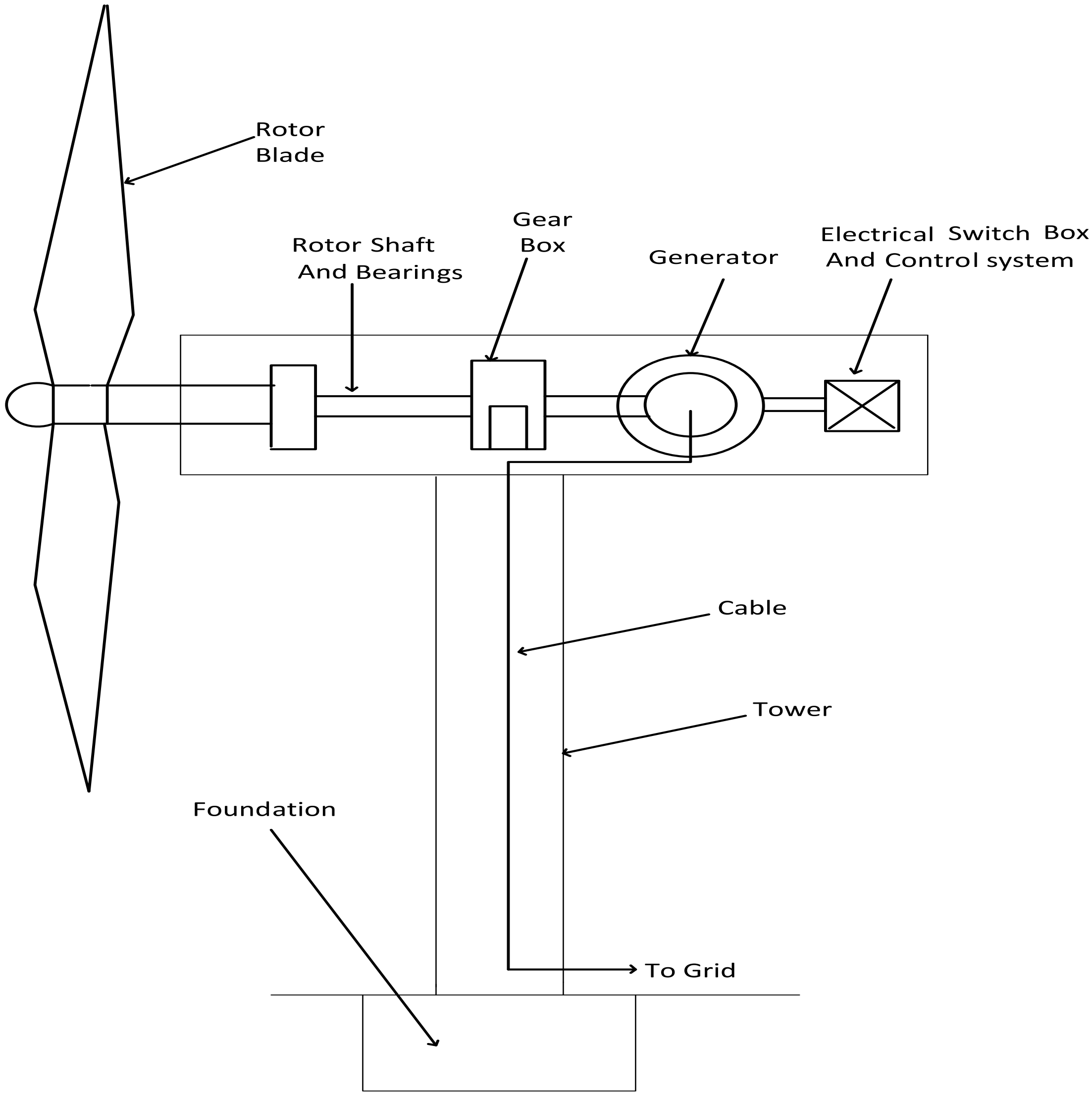

Figure 3.7 Horizontal Axis Wind Turbine

3.2.2 Vertical Axis Wind Turbines

In vertical axis wind turbines, the rotor shaft is arranged vertically. The main advantage with this type of turbines is that the turbine may not point to the direction of wind to be productive and there is no need of yaw mechanism [3].

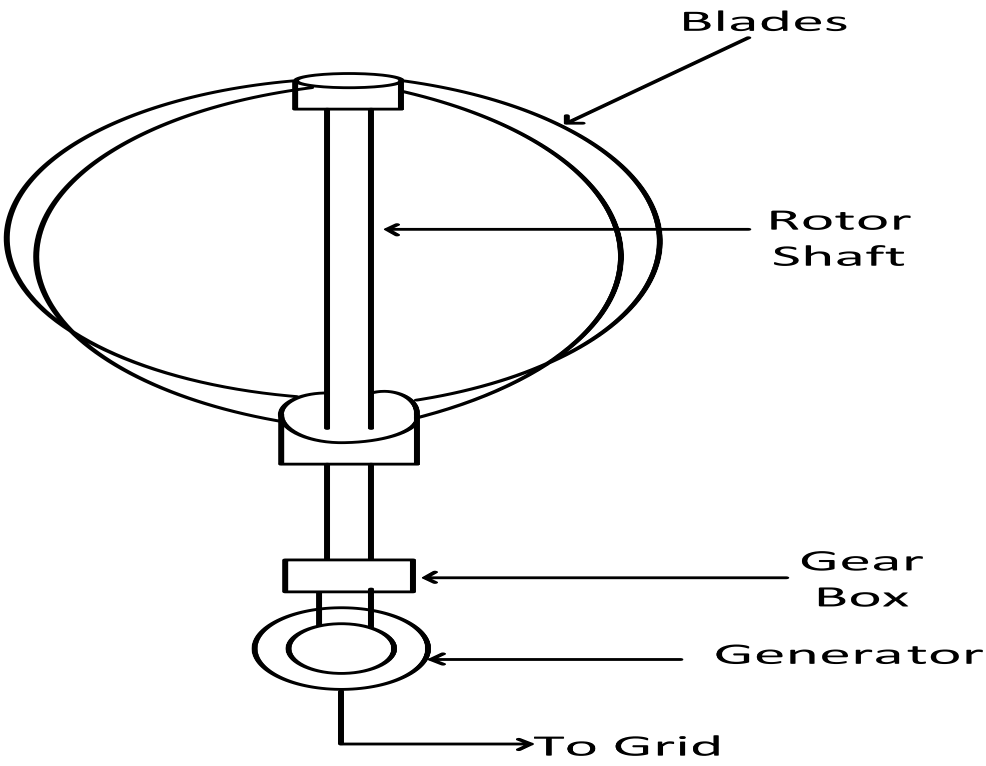

Figure 3.8 Vertical Axis Wind Turbine

The ease of maintenance is achieved as the gear box and generator is placed closer to ground and can be accessed easily for repair or maintenance. The main drawbacks of VAWT include low rotational speed and very high cost of drive train as torque is high, and coefficient of power is also very low.

3.3 WIND TURBINE PERFORMANCE PARAMETERS

Some of the important performance parameters are described below which are associated with wind turbines. Study of these parameters is necessary for control of a wind turbine model.

3.3.1 Tip Speed Ratio (TSR)

Tip Speed Ratio also denoted by λ is the ratio of rotor's blade tip velocity to the incoming air flow [37].

$$\lambda = \frac{\omega\ R}{V_w} \tag{3.1}$$

Where, ω = speed of turbine in radian per second

R = rotor radius in metres

V_w = wind speed in meter per second

3.3.2 Coefficient of Performance (C_p)

The ratio between the mechanical power extracted by turbine rotor and that of the undistributed air stream is called coefficient of performance [4].

$$C_p = \frac{P_r}{P_o} \tag{3.2}$$

C_p or coefficient of power or coefficient of performance designates the efficiency of turbine blades to capture power from the wind. It describes that how much chunk of power is snapped from wind to the blades of turbine. 59.3 percent is the theoretical boundary of the power coefficient and that limit is known as betz limit.

The formula for calculating C_p [24] is

$$C_p\ (\lambda,\beta) = C_1[\frac{C_2}{\lambda_i} - C_3\ \beta - C_4]e^{\frac{-C_5}{\lambda_i}} + C_6\ \lambda \tag{3.3}$$

Where,

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\ \beta} - \frac{0.035}{\beta^3 + 1} \tag{3.4}$$

Where, λ = tip speed ratio

β = Pitch angle (in degree)

3.3.3 Solidity

The ratio of projected area of blade to the rotor swept area of wind is known as solidity. Rotor swept area is the intercepted area by the wind [4].

$$\text{Solidity} = \frac{\text{projected area of blade}}{\text{rotor swept area}} \tag{3.5}$$

Basically solidity is associated with speed and torque of a turbine. In case of water pumping high torque and low speed is required which gives high solidity. Low solidity rotors are designated with high speed and low torque which is basically used in electrical power generation.

3.4 CONTROL SCHEMES FOR WIND TURBINES

The main aim of wind turbine is to capture maximum power from the wind and in any dire circumstances the safety of wind turbine can't be compromised so utmost care is taken to safeguarding wind turbine as well as to takeout maximum energy from wind [4]. When wind velocity is very high, in that case, the power absorbed by turbine should be restricted which is achieved by regulating the forces acting upon the rotor. Some techniques are employed to do so which are described below:

3.4.1 Pitch Control

In this control, blades of turbine are twisted into or out the wind. Deviation of force exerted by the wind on the rotor shaft results in limiting that force, hence control of wind turbine is achieved [43]. At higher wind speeds the power output can be limited to the rated power of generator using pitch control. The advantages of pitch control over other controls are:

- Alternative stop of turbine is achieved.
- Aided start-up and
- Power control is perfect with pitch control of turbine blades.

The disadvantages include the complexity of the system and power fluctuations are more when the wind speeds are high.

3.4.2 Stall Control

Stall control of wind turbine is of two types i.e. passive stall control and active stall control [43]. Active stall control is better in performance than passive stall control.

3.4.2.1 Passive Stall Control

The informal method of controlling is stall control and it takes place when the winds cross a certain limit that is at higher wind speeds. A lift force is exerted on the rotor which may stop the turbine and hence the turbine remains in a allowable speed range. The turbine remains safe and secure by that control at very high wind speeds. The efficiency of turbine is lower when compared with theoretical value in case when the wind speed is low.

3.4.2.2 Active Stall Control

The replacement of passive stall control is active stall control. For controlling the stall of blade actively instead of passive stall control pitching is used. This case is somewhat same as the pitch control, as blades are pitched in the same manner both at higher or lower wind speeds, except that the orientation of pitching of blades is in opposite direction.

Power fluctuation is less in this case and hence smoother limited power is obtained. Differences in air density are also compensated in active stall control. System can be stopped in case of emergencies and restarted again easily.

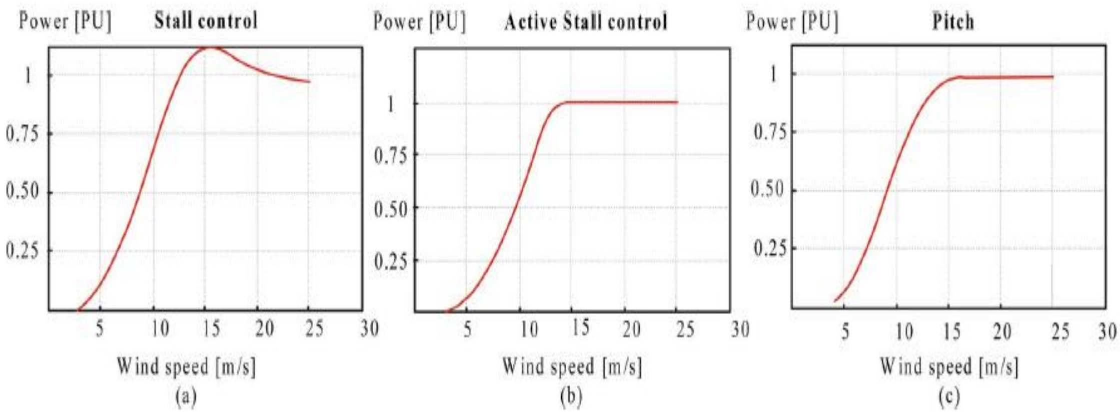

Figure 3.9 (a) Stall Control, (b) Active Stall Control, (c) Pitch Control

3.5 MODELLING OF WIND TURBINES

Modelling of wind turbines is carried out and its torque and power equations which include different performance parameters like tip speed ratio and coefficient of power are described. Different characteristics of wind turbine are plotted and studied with the help of these equations.

3.5.1 Mathematical Modelling of Wind Turbine

For thorough understanding of wind turbine operation knowledge of fluid mechanics is necessary. To drive the blades of turbine wind is necessary. The kinetic energy of wind is converted into mechanical energy as the turbine blades move through air and this drives the coupled generator which produces electrical power [3].

The kinetic energy of wind is given as:

$$E = \frac{1}{2} m V_w^2 \tag{3.6}$$

Where,

m = mass of air in kilogram,

V_w = wind speed in meter per second

But the expression of mass can be written as

$$m = \rho A V_w t \tag{3.7}$$

Where,

ρ = air density (1.225 kg/m^3)

A = the area through which the wind passes through in a given time 't'

Substituting value of equation (3.6) in equation (3.5), then the value of kinetic energy becomes,

$$E = \frac{1}{2} \rho A t V_w^3 \tag{3.8}$$

The power in the flow of air is given by

$$P_{air} = \frac{1}{2} \rho A V_w^3 \tag{3.9}$$

Above equation gives the available power in the wind but the turbine power is reduced by a coefficient C_p known as power coefficient.

$$C_p = \frac{P_{Wind\ Turbine}}{P_{air}}$$

$$P_{Wind\_Turbine} = C_p \times P_{air} = C_p \times \frac{1}{2} \rho A V_w^3 \tag{3.10}$$

The value of power coefficient is 59.3% and is known as Betz limit. In practical wind turbines the value of C_p remains between 25 – 45%. The power speed curve defines the relation between rotor speed and mechanical power taken out from the wind at different wind speeds.

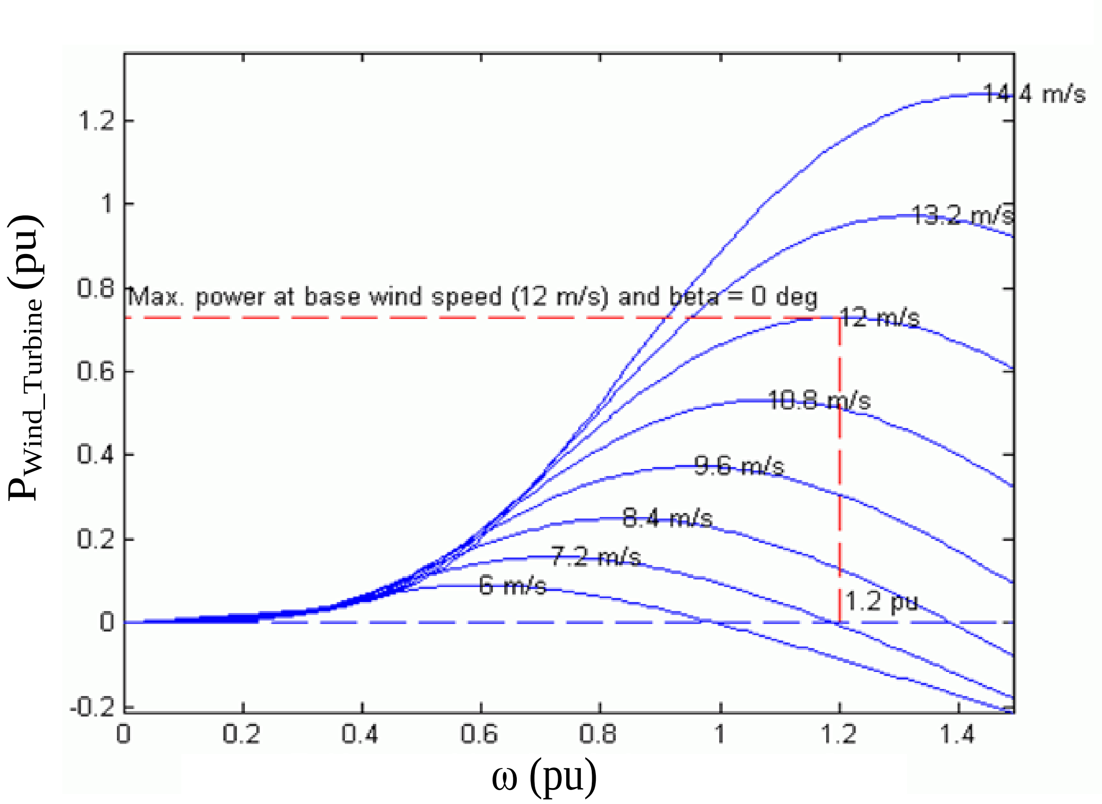

Figure 3.10 Turbine Power versus Turbine Speed Curve

(Figure source: www.mathworks.com)

For different wind speeds there is a favourable rotor speed at which most of the power is taken out of the wind. These curves are represented by C_p – λ curve which a single dimensionless characteristic curve as shown in figure 3.11. The value at which coefficient of power has maximum value gives the maximum power which can be extracted from the wind and wind turbines are made to work at maximum power coefficient using different techniques.

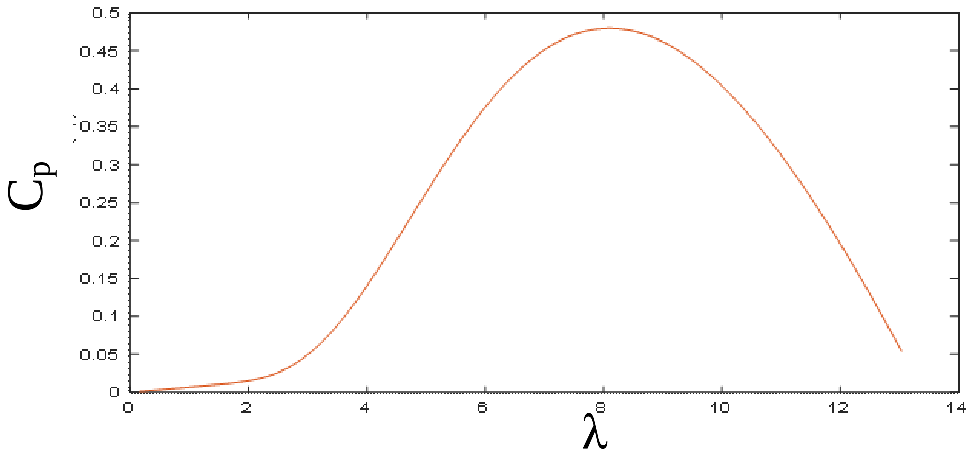

Figure 3.11 Power coefficient versus Tip Speed Ratio Curve

The mechanical torque of a wind turbine is given as [23-24]:

$$P_{Wind\_Turbine} = T_{Wind\_Turbine} \times \omega \tag{3.11}$$

Now substituting wind turbine power equation i.e. (3.10) into equation (3.11),

$$T_{Wind\_Turbine} \times \omega = C_p \times \frac{1}{2} \rho \, A \, V_w^3 \tag{3.12}$$

Where, $A = \pi \times R^2$ = Area covered by rotor blades (in m^2)

In equation (3.1), tip speed ratio or λ is already defined as

$$\lambda = \frac{\omega \times R}{V_w}$$

From above equation 'ω' can be defined as

$$\omega = \frac{\lambda \times V_w}{R} \tag{3.13}$$

Substituting value of ω in equation (3.12), we get

$$T_{Wind\_Turbine} = \frac{Cp \times \frac{1}{2} \rho \, A \, V_w^3 \times R}{\lambda \times V_w}$$

Substituting, $A = \pi \times R^2$, the final equation becomes

$$T_{Wind\_Turbine} = \frac{Cp \times \frac{1}{2} \rho \, \pi \, V_w^2 \times R^3}{\lambda} \tag{3.14}$$

The above equation describes the value of torque of a wind turbine [37]. The torque equation is also dependent on power coefficient as is power equation of a wind turbine. The torque speed characteristic of wind turbine is the one which is to be emulated with fixed pitch of rotor blades using a separately excited dc motor. This is achieved by controlling the armature voltage of a dc motor feeding it through a converter whose pulses are dependent on the wind turbine model.

3.5.2 Matlab Simulation of Wind Turbine

Simulation of wind turbine is achieved in Matlab/Simulink environment and the subsystems are discussed.

3.5.2.1 Simulink Model of Tip Speed Ratio Control

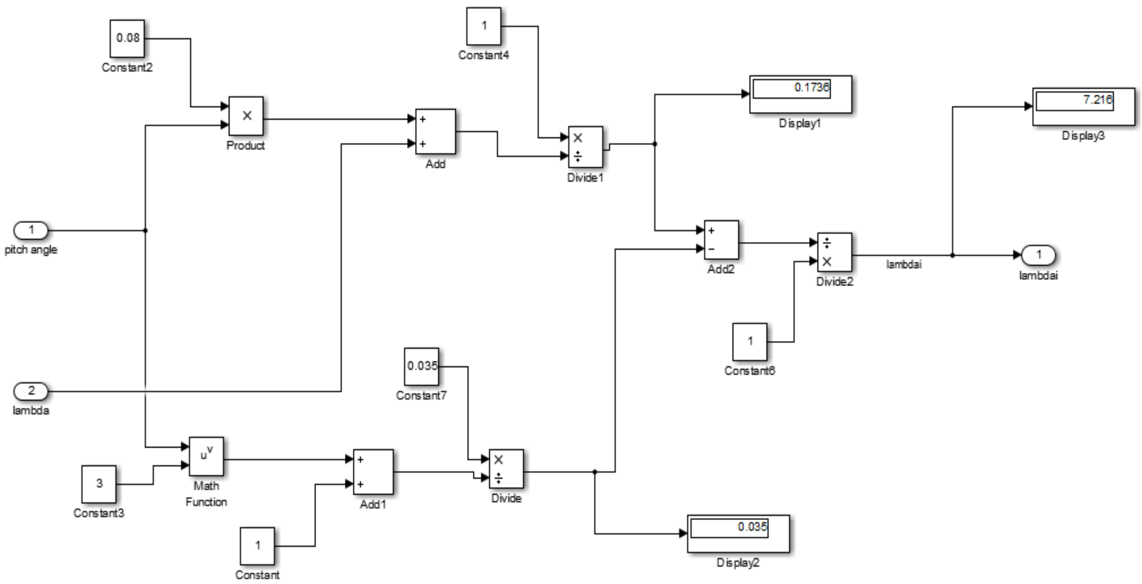

Figure 3.12 Simulink Model of Tip Speed Ratio Control

In this subsystem, β represents pitch angle and λ represents tip speed ratio. Pitch angle is taken as zero degrees and value of λ depends upon speed of turbine, radius of turbine blades and wind speed. Radius of turbine blades is 3 metres.

3.5.2.2 Simulink Model of Power Coefficient of Wind Turbine

Coefficient of power in wind turbine defines the percentage of wind power which can be taken out of the wind. The maximum value of power coefficient is 59.3% and is known as betz limit.

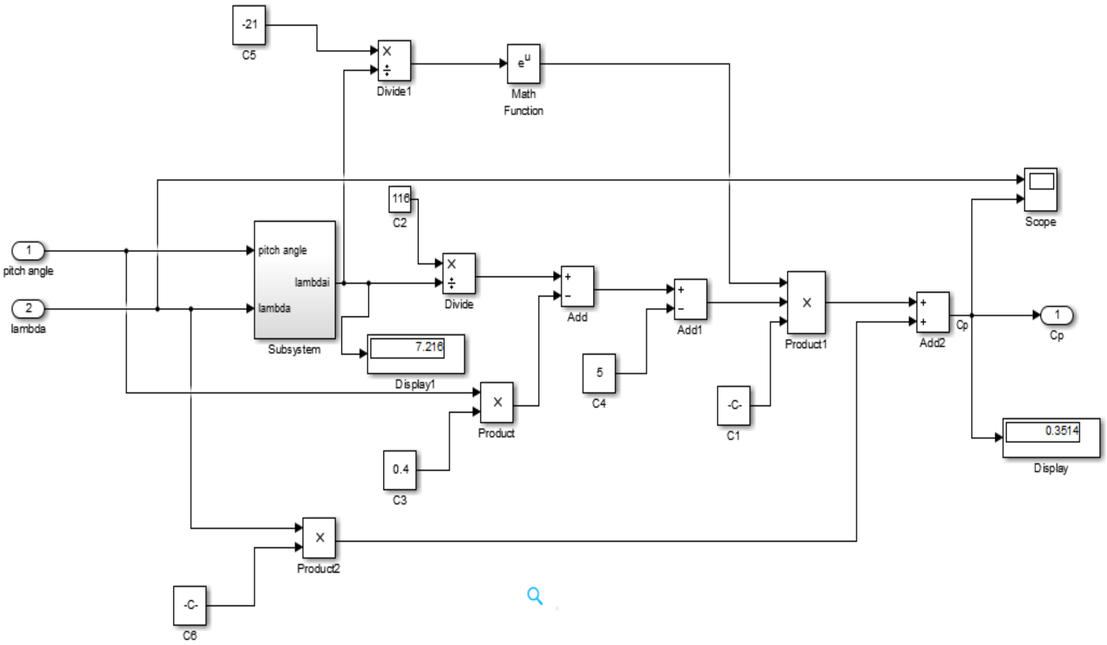

Figure 3.13 Simulink Model of Power Coefficient of Wind Turbine

The formula for power coefficient of wind turbine is given as

$$C_p\,(\lambda,\beta) = C_1[\frac{C_2}{\lambda_i} - C_3\,\beta - C_4]e^{\frac{-C_5}{\lambda_i}} + C_6\,\lambda$$

The value of constants used from C_1 to C_6 are taken as

$C_1 = 0.5176$	$C_2 = 116$	$C_3 = 0.4$	$C_4 = 5$	$C_5 = 21$	$C_6 = 0.0068$

Table 1 Value of Constants in coefficient of power

The performance of power coefficient defines the effectiveness of a wind turbine on scale of how much power is absorbed and utilised from the wind by the wind turbine.

3.5.2.3 Simulink Model of Wind Turbine

Figure 3.13 shows an overall wind turbine model with pitch angle always at zero degrees. Wind speed is an input parameter for the wind turbine model and hence with variations in wind speed, output in the form of power and torque is taken out from the wind turbine model which is dependent on performance parameters like power coefficient and tip speed ratio.

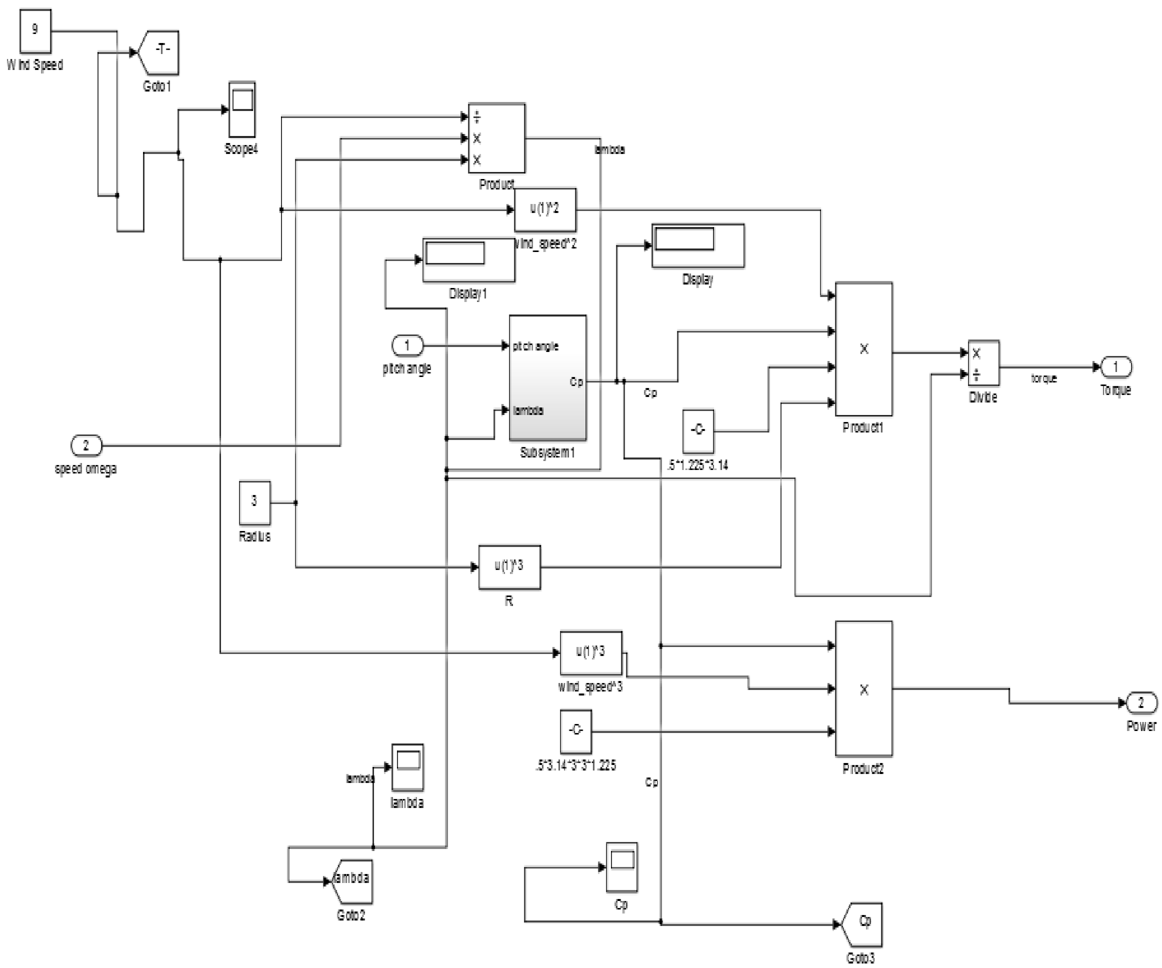

Figure 3.14 Simulink Model of Wind Turbine

The wind turbine generates the maximum value of power when the value of coefficient of power is maximum hence for a efficient wind turbine the value of power coefficient is of prime importance and should be as high as possible with betz limit.

3.6 SIMULATION RESULTS

Modelling and simulation of wind turbine in Matlab/Simulink is carried out to study the characteristics of a wind turbine with variable wind speed. A wind turbine with rotor blade radius of 3 meters, maximum coefficient of power is 0.48, air density is 1.225 Kg/m^3 and gear ratio of 7.6 is being considered for simulation study.

3.6.1 Turbine Power-Speed Characteristics

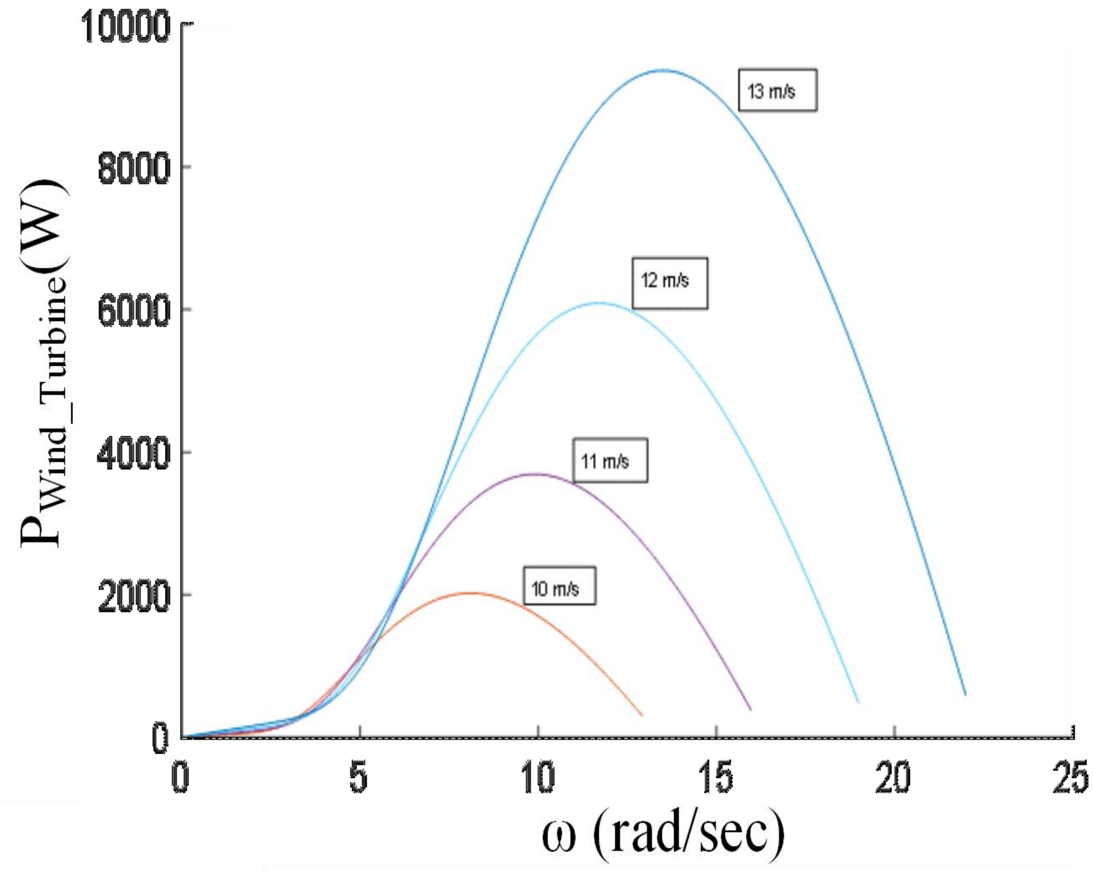

Figure 3.15 Turbine Power Speed Characteristics

Figure 3.14 shows turbine power-speed characteristics of the wind turbine model simulated. At starting when turbine speed is low i.e. about 5 rad/sec, the power generated by the wind turbine is also very less because the value of power coefficient is very low at starting of wind turbine. As the power coefficient increases, the value of power generated by turbine increases and reaches maximum power when power coefficient is at its peak value. After reaching its peak value the power coefficient decreases thereby decreasing the value of power generated. The characteristics of wind turbine are simulated on different wind speeds. At wind speed of 13 m/s the output power of turbine is maximum at turbine rotor speed of 14 rad/sec as coefficient of power is at its peak with value of 0.48 at this instant of time.

3.6.2 Turbine Torque -Speed characteristics

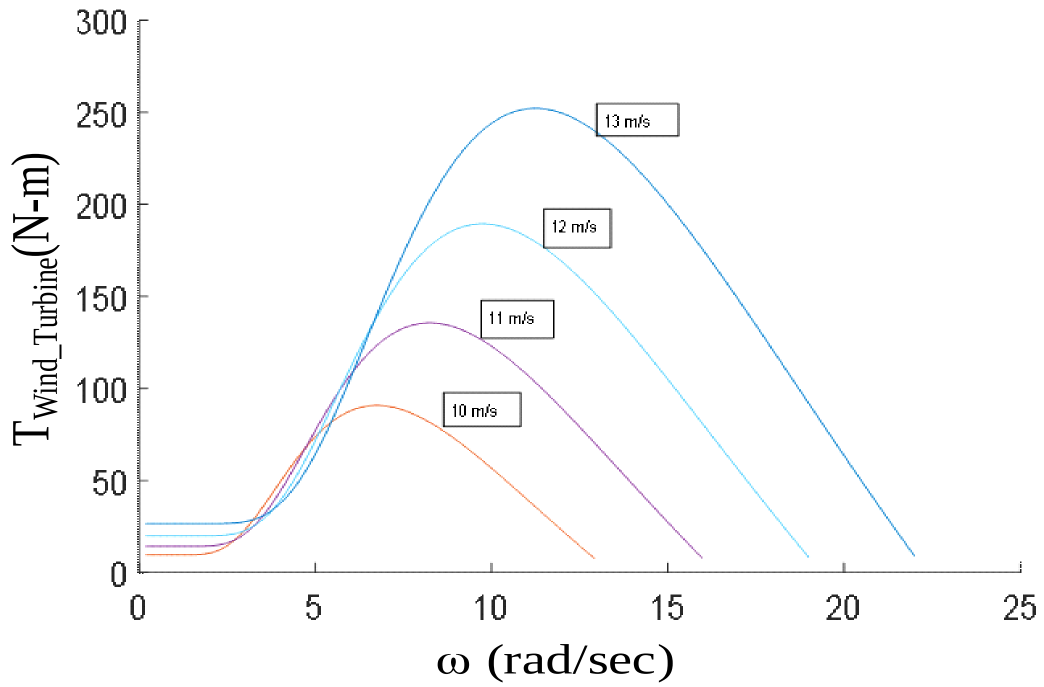

Figure 3.16 Turbine Torque-Speed Characteristics

Figure 3.5 shows torque-speed characteristics of the wind turbine model used in the simulation. At starting of wind turbine, the torque has some value as at low rotor speed of turbine, small power is generated and this low speed and low power give some value of turbine torque at starting. The power coefficient decides the maximum value of torque as decided in case of generated turbine power and at its peak, maximum torque is generated. With variable wind speeds different characteristics of wind turbine are plotted and at 13 m/s wind speed, torque generated by wind turbine is maximum.

3.7 CONCLUSION

The main components of a wind energy conversion system are wind turbines, generators and power converters. Wind turbine characteristics are dependent on many performance parameters and the simulation results show the exact torque-speed and power-speed characteristics of a standard wind turbine.

CHAPTER-IV

MODELLING AND CONTROL OF WIND TURBINE EMULATOR

4.1 GENERAL

As wind power establishments are raising at a very fast rate, structures are developed which are close to wind energy systems. Due to this, equipments which simulate the operation and purpose of wind turbine are set up in laboratories [20]. The basic aim of this type of equipments is to determine static and dynamic characteristics of an actual wind turbine and hence they are known as wind turbine emulators. Wind turbine emulators are evolved using different types of control practices and motors. The different machines like induction motors, DC motors and sometimes synchronous motors are used as the mechanical prime movers in wind turbine emulators. When separately excited DC motors are used in wind turbine emulators then the control techniques used are voltage control technique or field voltage control technique to get the characteristics of a wind turbine. Permanent magnet synchronous motors are employed in some simulators as a prime mover with a voltage source converter. There is number of generators as well as number of prime movers used in wind turbine emulators. Induction generators are mainly used with less use of DC and synchronous generators.

4.2 WIND TURBINE EMULATOR

Wind turbine behaviour is emulated using a dc motor and buck converter. Modelling of dc machine and converter is described in this chapter.

4.2.1 Modelling of Separately Excited DC Motor

In a separately excited dc motor separate supply is provided to field and armature windings. Field winding facilitates field flux to armature. As the rotor rotates which is carrying current, a back EMF and torque is generated by armature to equalise the load torque at a given speed. The field and armature both are provided with different supply and hence field current and armature current does not depend on each other and change in armature current does not vary the field current. The value of field current is normally very less than armature current [44]. The total induced EMF in the motor is given by

$$e_b = k\ \Phi\ \omega_m(t) = K_b\ \omega_m(t) \qquad (4.1)$$

Where, $k = \frac{P\ Z}{2\ \pi\ A}$

P = number of poles,

Z = Total number of conductor,

A = number of parallel paths,

(A = 2 for wave winding and A = P for lap winding)

Φ = flux per pole in Weber,

ω_m = speed of motor (rad/sec)

e_b = induced back EMF

K_b = EMF constant.

The required magnetic field for working of motor is generated by field current.

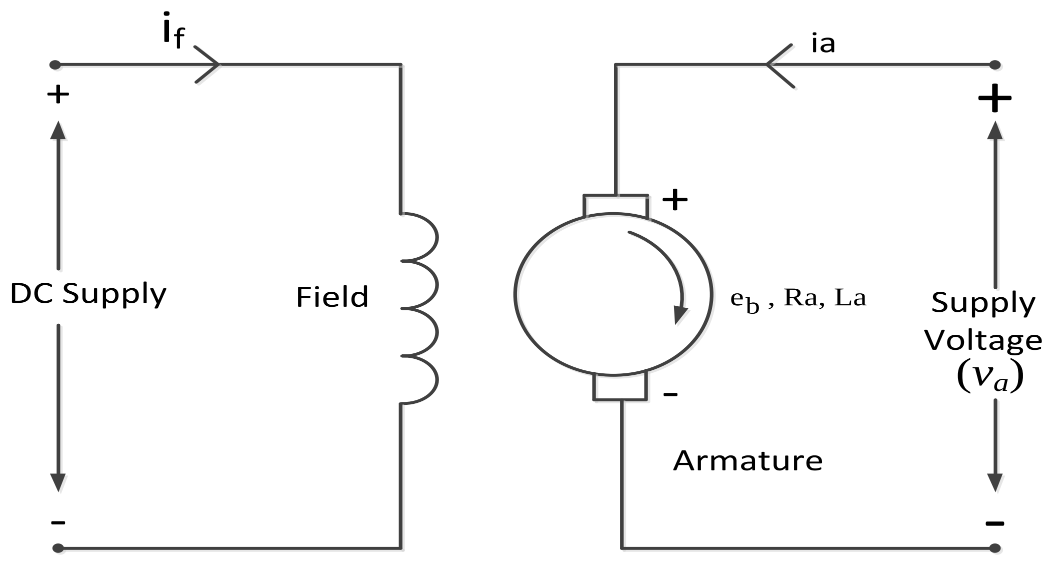

Figure 4.1 Circuit Diagram of DC Motor

By applying KVL [44-45]

$$v_a = e_b + i_a(t)\,R_a + L_a \frac{di_a(t)}{dt} \tag{4.2}$$

Where, v_a = applied dc voltage

R_a = armature resistance in ohm

L_a = armature inductance in Henry

i_a = armature current in ampere

For constant field current, the flux remains constant in a separately excited dc motor. The torque equation of a dc motor is given as

$$T = k\,\Phi\,i_a(t) = K_t\,i_a(t) = J\frac{d\omega_m(t)}{dt} + B\,\omega_m(t) \tag{4.3}$$

Where, J = inertia of motor in kg/m^2

B = Friction constant

Now, changing equations 4.1, 4.2 and 4.3 into Laplace form,

$$e_b(s) = K_b\,\omega_m(s) \tag{4.4}$$

$$v_a(s) = (R_a + L_a\,s)\,i_a(s) + e_b(s) \tag{4.5}$$

$$T(s) = (B + J\,s)\,\omega_m(s) = K_t\,i_a(s) \tag{4.6}$$

By using equations 4.1-4.6, the armature voltage control system function block can be designed which is shown in figure 4.2.

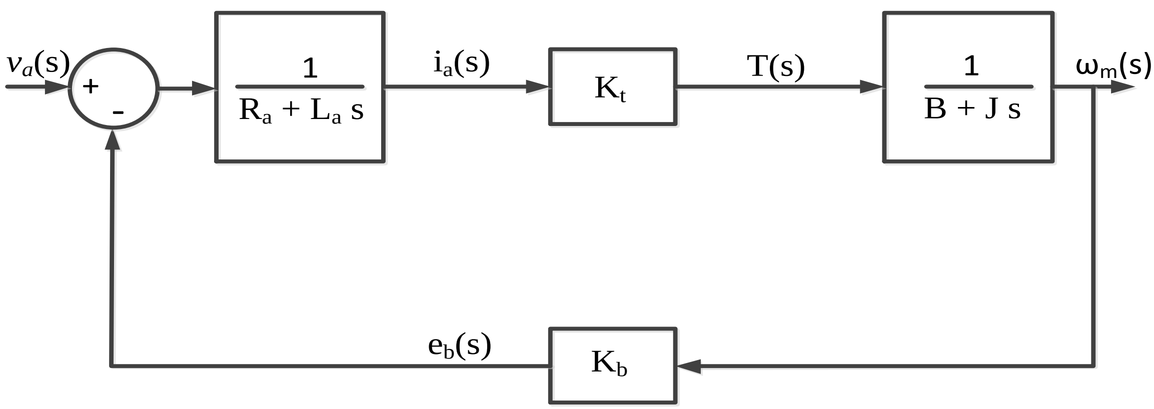

Figure 4.2 DC Motor Armature Voltage Control System Function Block Diagram

The transfer function in the form of speed with respect to input voltage can be written as follows.

$$G(s) = \frac{\omega_m(s)}{v_a(s)} = \frac{K_t}{(Ra + La\ s)(B + J\ s) + K_b\ K_t} \qquad (4.7)$$

Flux Φ is taken as constant because field circuit is excited with a constant voltage and from equations 4.1, 4.2, and 4.3,

$$e_b = v_a - i_a R_a$$

$$k\ \Phi\ \omega_m = e_b = v_a - i_a R_a$$

$$\omega_m = \frac{v_a}{k\ \Phi} - \frac{i_a\ Ra}{k\ \Phi} \qquad (4.8)$$

From equation 4.3, $T = k\ \Phi\ i_a$

$$i_a = \frac{T}{k\ \Phi}$$

Substituting value of i_a in equation 4.8,

$$\omega_m = \frac{v_a}{(k\ \Phi)} - \frac{T\ Ra}{(k\ \Phi)^2} \qquad (4.9)$$

Now by using equation 4.9, the three parameters which govern the speed of dc motor are armature current, armature resistance, applied voltage and field flux. Thus three methods are there which can be used for regulating the speed of dc motor.

A. Voltage control method
B. Flux control method

A. Armature Terminal Voltage Control

In this method of speed control, a fixed voltage is imprinted on field of the motor and various voltages is provided to armature through switchgear by joining it athwart to one of many different voltages. The armature speed is governed by these different voltages due to the direct proportionality. The intermediate speeds are achieved by shunt field regulator and this is the best method for separately excited dc motors. As a fixed voltage is provided at field side, the flux Φ becomes constant and armature resistance is always a constant.

In normal working of dc motor, the drop against the armature resistance is very small compared to e_b and therefore:

$$e_b = v_a$$

$$\text{Since, } e_b = k\,\Phi\,\omega_m$$

And in this case k and Φ are constants, so the equation becomes

$$\omega_m = \frac{v_a}{K}, \qquad \text{as} \qquad k\,\Phi = K$$

This means that speed of motor is directly proportional to the applied voltage at the motor terminals and hence we from above equation we can interpret that

- The speed of motor varies linearly with applied voltage V provided that the flux Φ is constant.
- As the terminal voltage is raised the speed surges and vice versa is also true.

B. Flux Control Method

When rated voltage is applied across the field coil of dc machine, the field coil will generate the rated flux. And if we provide a external resistance in series with field coil, the rated field current can be varied and eventually it will lead to vary the flux. The field can't be made stronger so by introducing a resistance field current will reduce and hence the flux will reduce. The speed of dc motor and flux are inversely proportional to each other so speeds above base speeds are obtained by using this method of speed control.

4.2.2 Operation of DC to DC Converter

To get the characteristics of a wind turbine the dc motor has to be controlled in such a way that the armature terminal voltage should change as per the governing wind turbine model and this motor control action is achieved using a dc to dc converter. The gate pulse changes as per wind turbine model and hence the armature voltage is also changed in accordance with it and smooth emulation of characteristics of wind turbine is achieved. The dc to dc converter can be of two types i.e. buck converter and boost converter.

Buck converters are used to produce variable dc output voltage which is lower than the input dc voltage. Buck converter is also known to us as step down converter or DC to DC converter. Since input voltage is greater than output voltage in buck converter then the input current should be lower than the output current to satisfy conservation of energy law. Therefore in case of buck converter

$$v_a > v_o \text{ and } i_a < i_o$$

It can be used where there is no need of electrical isolation between output and switching circuit. The working principle of buck converter defines that the inductor will resist any sudden change in input current. The inductor stores magnetic energy when the switch is ON and discharges it when switch is closed. The capacitor at the output side is assumed to be large enough so that the time constant of output stage (t = RC) is high. High or large time constant as compared with switching period provides a constant output voltage.

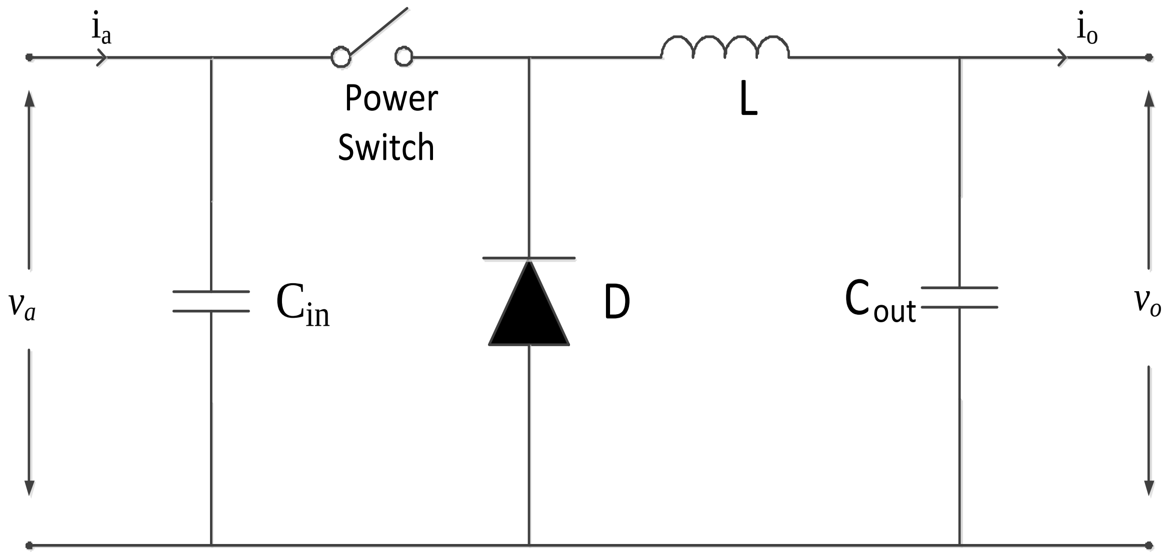

Figure 4.3 Circuit Diagram of Buck Converter

When the switch in buck converter is closed, the voltage that appears across the inductor is v_a–v_o. The current in the inductor will rise at a rate of $(v_a - v_o)/L$. At this point of time the diode is reversed biased and no conduction through it takes place. With opening of switch, the voltage across inductor is reversed and the current through inductor decreases.

When switch is opened, the inductor won't let the direction of current to change and hence keep the same current flowing. So the current still flows through the inductor and into the load. Now the diode is forward biased and provides the return path to the diode current which is equal to the current flowing through the load.

Buck converter operates in two modes i.e. continuous conduction mode and discontinuous conduction mode. Both modes of operation are explained one by one for RLE load.

4.2.2.1 Continuous Conduction Mode:

In this mode the current through inductor never reaches zero i.e. before the starting of the switching cycle inductor partially discharges [49]. When switch is closed, then current i_{a1} flows into the load and is known as mode1 operation of chopper.

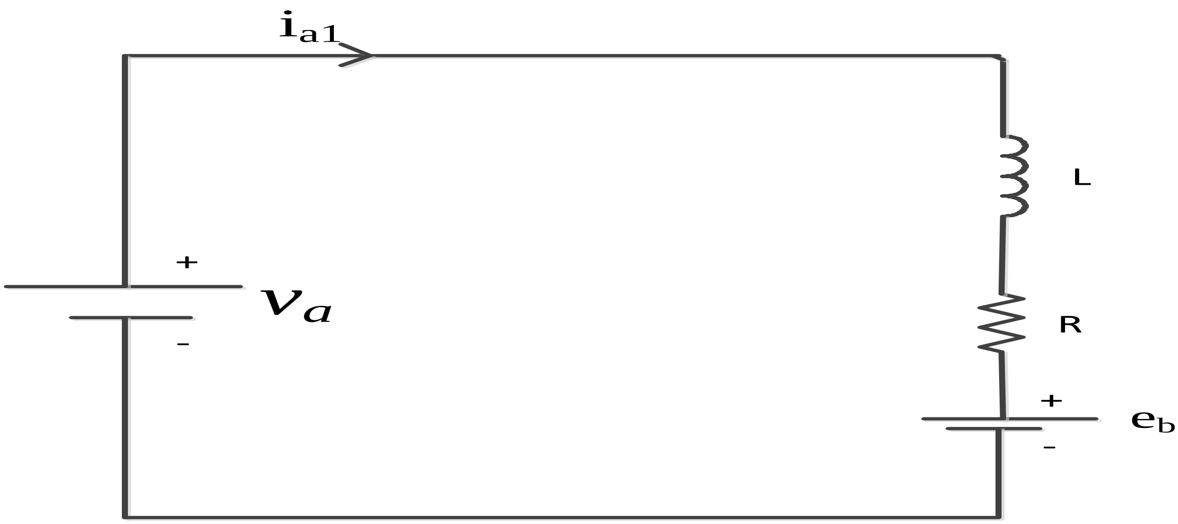

Figure 4.4 When switch is closed, Mode1 operation

When switch is opened, current i_{a2} flows in the load and is known as mode2 operation of chopper.

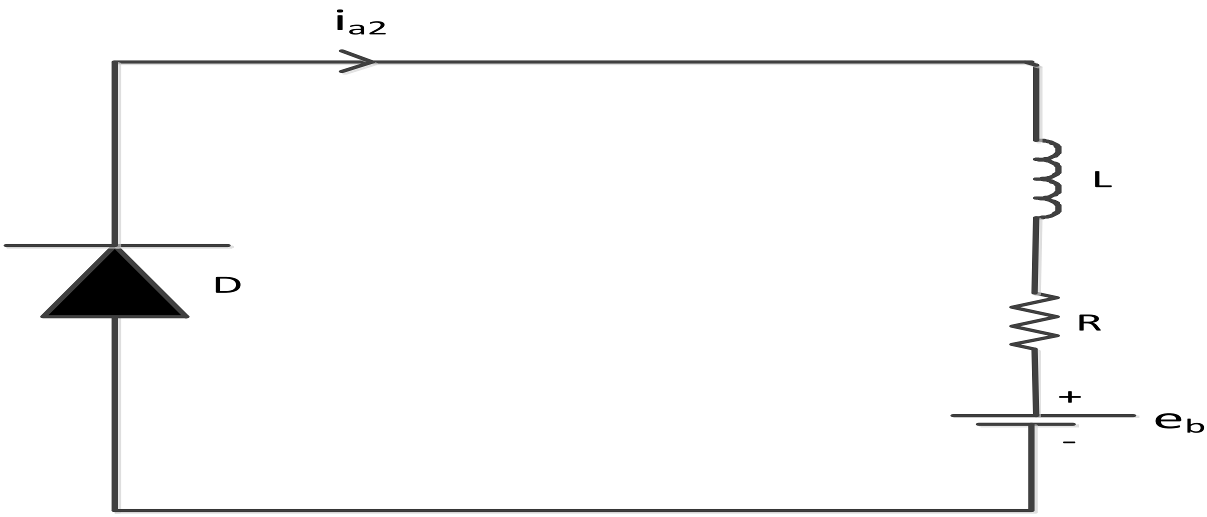

Figure 4.5 When switch is open, Mode2operation

For mode1 the load current can be found from

$$v_a = Ri_{a1} + L\frac{di_{a1}}{dt} + e_b$$

At t=0 the initial current i_{a1}=I_1 that gives the load current as:

$$i_{a1}(t) = I_1 e^{-tR/L} + \frac{v_a - e_b}{R}(1 - e^{-tR/L}) \quad (4.10)$$

This mode is valid for $0 \leq t \leq t_1$ (=kT); and at the end of this mode the load current becomes:

$$i_{a1}(t = t_1 = kT) = I_2 \quad (4.11)$$

The load current for mode2 can be found from:

$$0 = Ri_{a2} + L\frac{di_{a2}}{dt} + e_b$$

With initial current i_{a2} (t=0)= I_2 and redefining the time origin (i.e. t=0) at the beginning of mode 2 we have:

$$i_{a2}(t) = I_2 e^{-tR/L} - \frac{e_b}{R}(1 - e^{-tR/L}) \quad (4.12)$$

This mode is valid for $0 \leq t \leq t_2$ (=(1-k)T); and at the end of this mode the load current becomes:

$$i_{a2}(t = t_2) = I_3 \quad (4.13)$$

At the end of mode2 the converter is turned on again in the next cycle after time, T=1/f=t_1+t_2 under steady state condition, I_1= I_3. The peak to peak load ripple current can be determined from equation 4.21-4.24. From equations 4.21 and 4.22 I_2 is given by:

$$I_2 = I_1 e^{-kTR/L} + \frac{v_a - e_b}{R}(1 - e^{-kTR/L}) \quad (4.14)$$

From equation 4.23 and 4.24, I_3 is given by:

$$I_3 = I_1 = I_2 e^{-(1-k)TR/L} - \frac{e_b}{R}(1 - e^{-(1-k)TR/L}) \quad (4.15)$$

Solving for I_1 and I_2 we get:

$$I_1 = \frac{v_a}{R}\left(\frac{e^{kz}-1}{e^{z}-1}\right) - \frac{e_b}{R} \quad (4.16)$$

Where $z = \frac{TR}{L}$ is the ratio of the chopping and switching period to the load time constant:

$$I_2 = \frac{v_a}{R}\left(\frac{e^{-kz}-1}{e^{-z}-1}\right) - \frac{e_b}{R} \quad (4.17)$$

The peak to peak ripple current is:

$$\Delta I = I_2 - I_1$$

This after simplification becomes:

$$\Delta I = \frac{v_a}{R}\frac{1-e^{-kz}+e^{-z}-e^{-(1-k)z}}{1-e^{-z}} \quad (4.18)$$

The condition for maximum ripple:

$$\frac{d(\Delta I)}{dk} = 0 \quad (4.19)$$

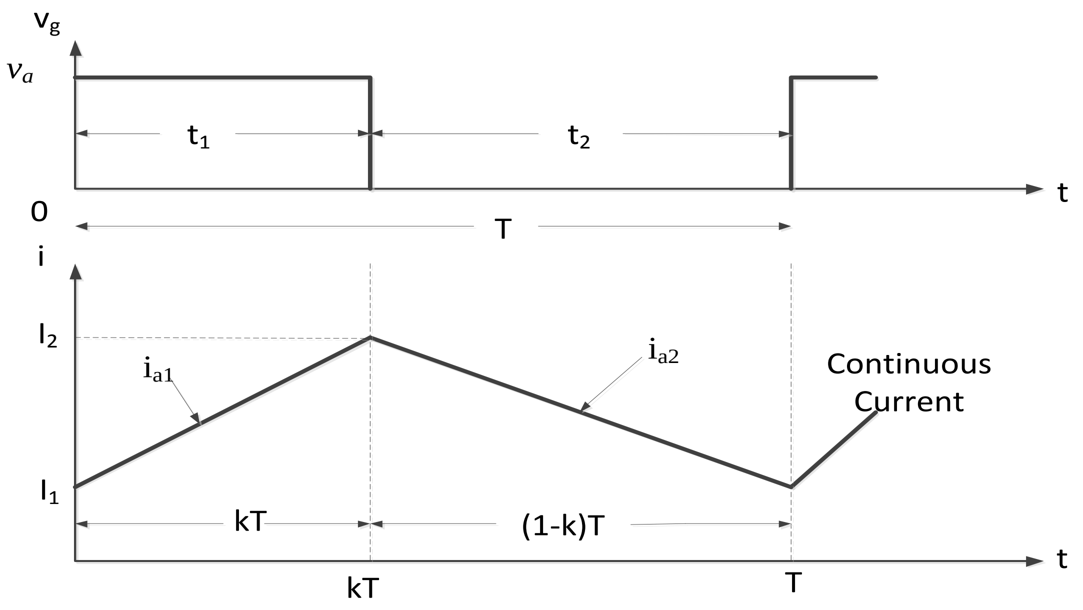

Figure 4.6 Waveform for continuous conduction mode

On simplifying the above equation we get, k = .50. Hence, if value of duty cycle is less than .5 then the chopper will operate in continuous conduction mode.

4.2.2.2 Discontinuous Conduction Mode:

In this mode the current through inductor reaches zero i.e. at the end of switching cycle the inductor discharge completely.

The equations from 4.21 to 4.30 remains same as in the condition discussed above. If k≥ .5 the chopper will operate in discontinuous conduction mode.

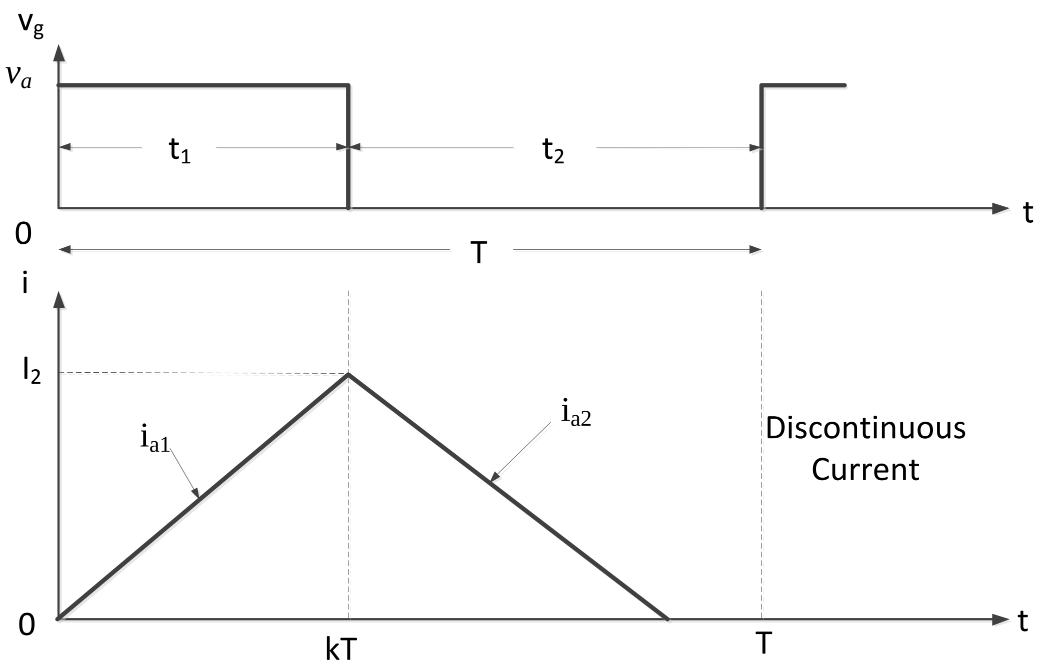

Figure 4.7 Waveform for discontinuous conduction mode

4.2.3 MATLAB MODEL OF DC TO DC CONVERTER

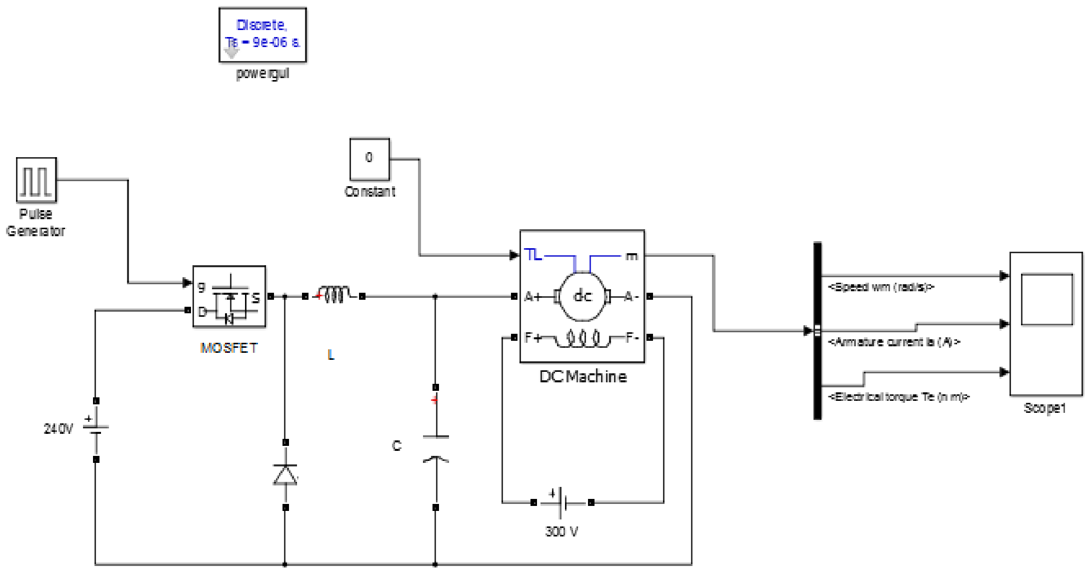

Figure **4.8** Matlab model of dc to dc converter

The dc source used at the buck converter terminal is of 240 V. The calculated value of inductor is 9.6 mH and value of capacitor used in simulation is 150 µH.

4.2.4 DESIGN OF DC TO DC CONVERTERS

Buck converter parameters are calculated using the formulas as described below [48].

4.2.4.1 Maximum Duty Cycle

The parameters of buck converter are calculated using the formulas described as follows:

Maximum Duty Cycle: $D = \frac{v_o \times \eta}{v_{a(max)}}$ (4.20)

Where, $v_{a(max)}$ = maximum input voltage

v_o = desired output voltage

η = efficiency of converter, e.g. estimated 85%

The energy dissipated has to be delivered by converter so the efficiency factor is also added in the above equation. By adding efficiency factor a more realistic duty cycle can be calculated. The inductor ripple current is to be calculated to know the maximum switch current.

4.2.4.2 Inductor Ripple Current

Inductor Ripple Current: $\Delta I_L = \frac{v_{a(max)} - v_o) \times D}{f_S \times L}$ (4.21)

Where, D = duty cycle calculated in equation 4.31,

f_s = minimum switching frequency of converter,

L = selected inductor value

4.2.4.3 Selection of Inductor Value

Now, the inductor value is selected if it is not provided in the datasheet. If the inductor value is high, the ripple current will be less and the output current will become high. The formula for estimating inductor value is

Inductor: $L = \frac{(v_a - v_o) \times v_o}{f_S \times v_o \times \Delta I_L}$ (4.22)

Where, v_a = input voltage

v_o = desired output voltage

f_s = minimum switching frequency

ΔI_L = inductor ripple current

In equation 4.32, the inductor ripple current cannot be calculated as the inductor value is not known. For calculating the inductor ripple current a good estimation is 20% to 40% of output current.

i.e. $\Delta I_L = (0.2 \text{ to } 0.4) \times i_{out(max)}$

Where, $i_{out(max)}$ = maximum output current

4.2.4.4 Selection of Diode

The forward current rating for diode can be calculated with the help of maximum output current.

$$i_f = i_{out(max)} \times (1 - D) \quad (4.23)$$

Where, i_f = average forward current of diode

D = maximum duty cycle calculated in equation 4.31.

Other than forward current rating the power dissipation of diode is also an important factor. The power dissipation of diode is given as

$$P_d = i_f \times v_f$$

Where, v_f = forward voltage of diode

4.2.4.5 Output Capacitor Selection

The minimum output capacitor value can be calculated as

$$C_{out(min)} = \frac{\Delta I_L}{8 \times f_s \times \Delta v_o} \quad (4.24)$$

Where, $C_{out(min)}$ = minimum output capacitance,

ΔI_L = inductor ripple current,

f_s = switching frequency

Δv_o = desired output voltage

The criterion on which the output capacitor is selected is output transient response and it is not driven by steady state ripple. The voltage deviation at output is that time which inductor takes to catch up with reduced or increased current needs.

4.3 ARMATURE CURRENT REGULATION OF DC MOTOR

4.3.1 Proportional Integral (PI) Control

PI is a combination of proportional and integral controller and the output of this controller can also be called an actuating signal which works on a error signal. PI controller is also known as feedback controller and it has some advantages such as it eliminates the offset, it increases the performance in steady state condition while eliminating the error and oscillations of the system. [50] While comparing the triangular signal and the output error from the current controller, the gating signal for the semiconductor devices are generated to operate the semiconductor switches. Figure 4.9 shows the block diagram representation of proportional and integral controller.

There are many ways to tune the PI controller and an automatic tuning can presented through the Ziegler-Nichols method. A simple rule to tune the PI is:

- Keep the integration part of the controller to zero.
- Now tune the proportional gain Kp of the controller until the desired result is obtained.
- Then increase the integrator part by reducing the value of K_p to the half of the actual value, and then turn slowly the values of K_p and K_I to find the desired results appropriately.

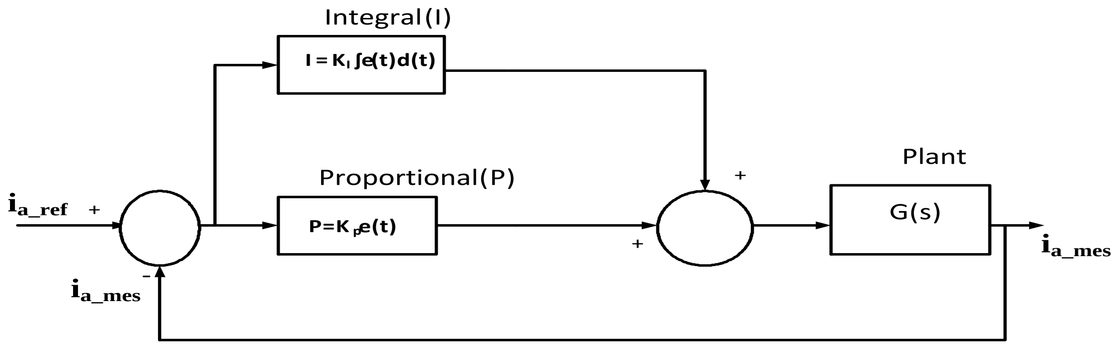

Figure4.9 Block diagram representation of proportional and integral controller

Mathematically we can design the controller as given below:

Output of controller=$K_p.e(t) + \frac{K_I}{T_I}\int e(t)dt$ (4.25)

e(t) = error signal = $i_{a\_ref} - i_{a\_mes}$

K_P = Proportional control gain

K_I = Integral control gain

4.3.2 Pulse Width Modulation (PWM) Controller

In this project, PWM wave is generated by first comparing the armature current (I_a) of the DC motor with the current that is retrieved from the torque current equation of wind turbine model. [49] The error so produced is fed to PI controller and then output is fed into saturation block, which keeps the wave between zero and one. Then, the output of saturation block is compared sawtooth carrier wave having time period of 0.5 ms .The output PWM wave is of constant magnitude and variable width. The width of the wave will vary depending on the value of load current or armature current.

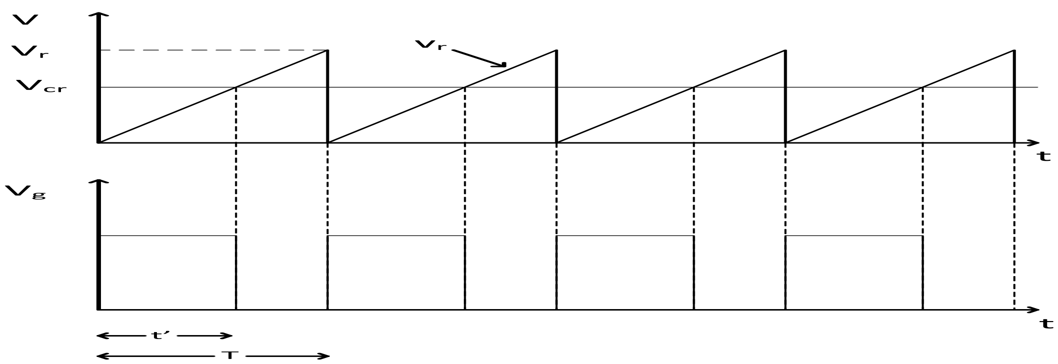

Figure 4.10 Comparing a reference signal with a carrier wave

The PWM wave generated on comparing a reference signal with a carrier wave is explained through the diagram in figure 4.10 [49]:

Where, t '= ON time of chopper,

T = Operating time period of chopper, And

t' = kT

where k is the duty cycle that can be generated by comparing a reference signal (v_r) with a sawtooth carrier signal (V_{cr}). The reference signal v_r is given by:

$$v_r = \frac{V_r}{T} t \tag{4.26}$$

Where, V_r = peak value of reference signal

At t = t', the reference signal equals carrier signal (v_{cr}) = V_{cr}.

Therefore, from equation 1

$$V_{cr} = \frac{V_r}{T} kT \tag{4.27}$$

Which gives the duty cycle k as,

$$k = \frac{V_{cr}}{V_r} = M \tag{4.28}$$

Where M is the modulation index. By varying the carrier signal v_{cr} from zero to V_{cr} the duty cycle k can be varied from zero to one.

The algorithm to generate PWM signal is as follows:

1. Generate a triangular waveform of period T as reference signal v_r and a carrier signal v_{cr}.
2. Compute these signals by comparator to generate the difference v_c - v_r and then a hard limiter to obtain a square wave gate pulse of width kT, which must be applied to switching device through an isolating circuit.
3. Any variation of v_{cr} varies linearly with the duty cycle k.

4.4 CONCLUSION

The governing equations of separately excited dc motor and buck converter design has been studied. Buck converter and PI regulator controls the entire system so that desired output can be obtained. Through pulse width modulation the gate pulses for buck converter switch is created which controls the armature voltage of dc motor and therefore in turn controls the speed of dc motor.

CHAPTER-V

DEVELOPMENT OF WIND TURBINE EMULATOR

5.1 MATLAB SIMULATION OF WIND TURBINE EMULATOR

A wind turbine emulator is being developed in Matlab/Simulink using a dc motor and dc to dc converter. The speed and torque control of dc motor is achieved through dc to dc converter to realise the characteristics of wind turbine driven PMSG. Emulation of torque-speed characteristics of a wind turbine is achieved by two ways. The first way is that from a numerical simulator a rotational speed is generated and by taking this speed as a reference, the speed of dc motor is controlled to get the required characteristics. This method of emulation is known as tracking speed model or pursuing speed model. The second method uses the speed of motor to generate a torque reference from the wind turbine model and this torque reference is changed into current reference and the reference current is compared with the actual armature current of the dc motor. The latter scheme is implemented in the thesis.

First a mathematical model of wind turbine is created using equations designed in chapter 3 (3.1-3.13). The inputs to the model are angular speed of turbine, pitch angle and speed of wind. With a gearbox the angular speed is applied to the wind turbine model. Figure 5.1 shows the detailed structure of a wind turbine emulator. From the mathematical model of wind turbine a electromagnetic torque reference is derived which is to be controlled using PI controller and figure 5.2 shows Matlab simulation of wind turbine emulator.

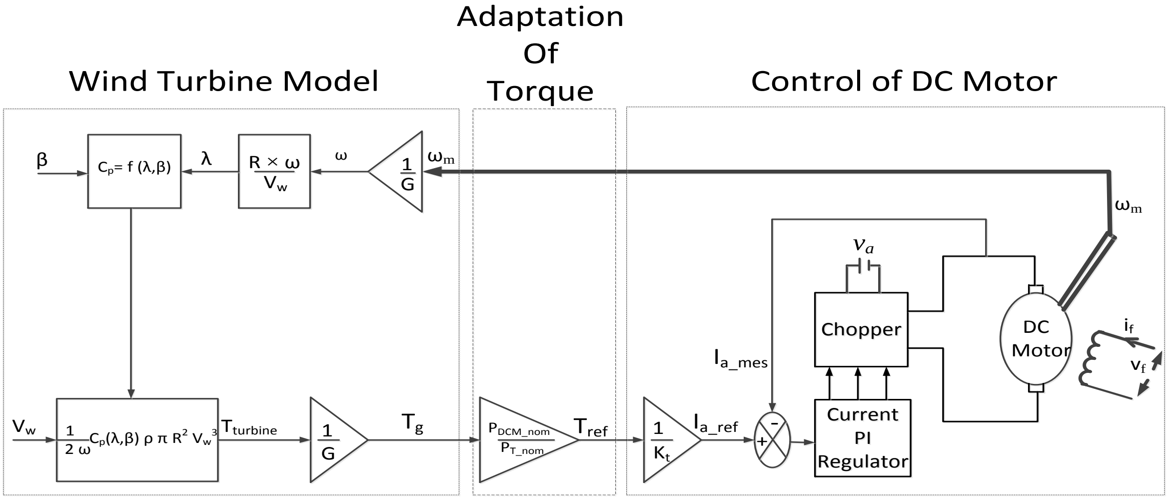

Figure 5.1 Detailed Structure of Wind Turbine Emulator

This adaptation of torque is made by the gain block which is the ratio of rated power of dc motor and that of wind turbine. An adaptation of magnitude of torque is achieved to reproduce actual profile of torque of wind turbine but on a lesser scale.

$$\text{Adaptation of torque} = \frac{Rated\ power\ of\ DC\ \ machine}{Rated\ power\ of\ Turbine} \tag{5.1}$$

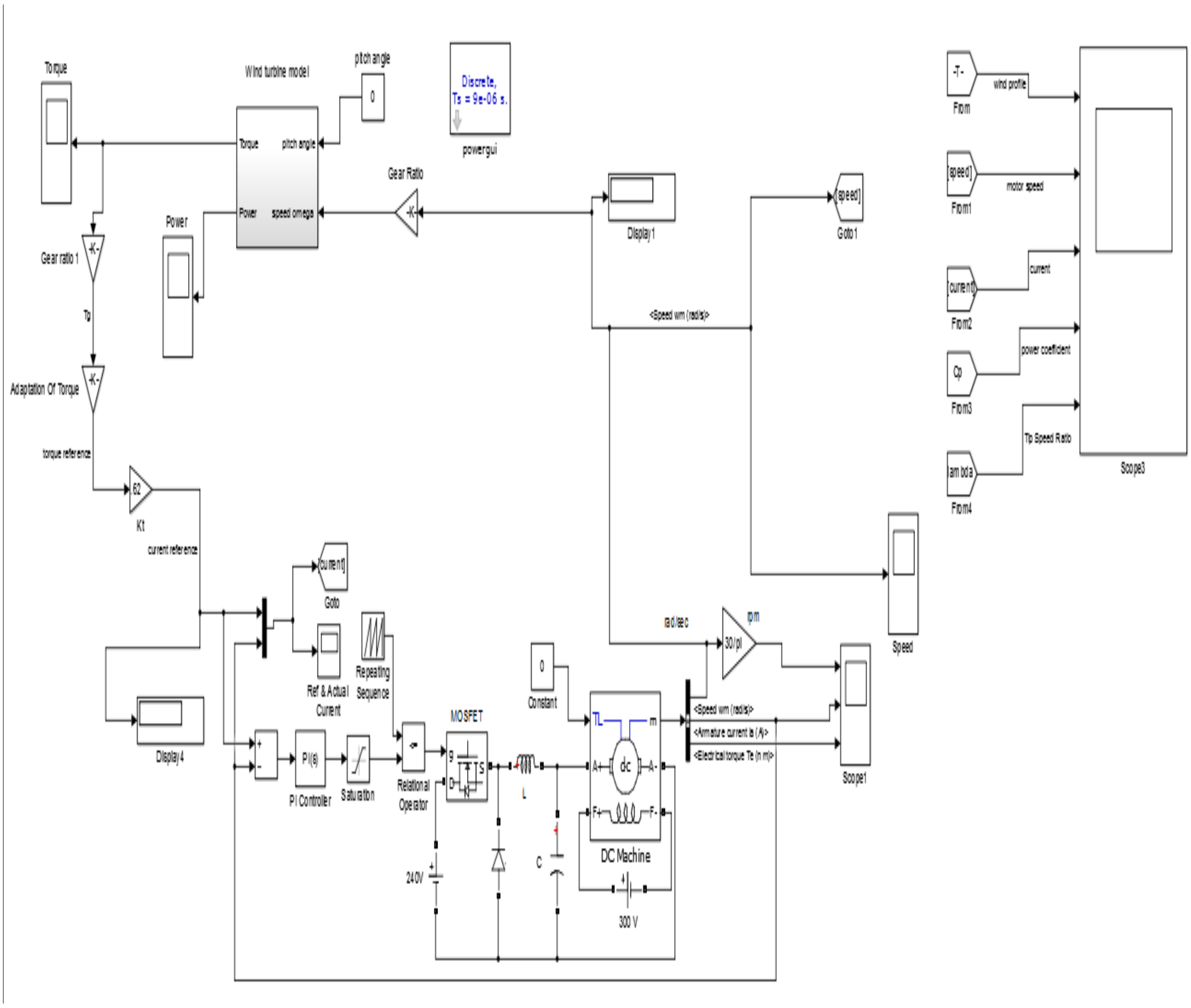

Figure 5.2 Matlab simulation of Wind Turbine Emulator

From the turbine model a reference torque is generated which is then multiplied with a suitable gear ratio and torque constant to get a reference current. This reference current is compared with the actual armature current of dc motor and the error is minimised using a PI controller. The proportional integral (PI) type of controller is used in this scheme because it is easy and very quick to implement. The output of PI controller block is then compared with a very high frequency signal (ramp) to generate pulse width modulated gate pulses to drive a IGBT/MOSFET. This converter controls the armature voltage of dc motor which in turn controls armature current in compliance with the reference current and hence slowly the system attains steady state.

5.2 SIMULATION RESULTS

Simulation study of a wind emulator is carried out by using a 3.73 kW, 240 V, and 183.26 rad/sec dc motor driven by a dc to dc (buck) converter.

5.2.1 Turbine Torque-Speed Characteristics

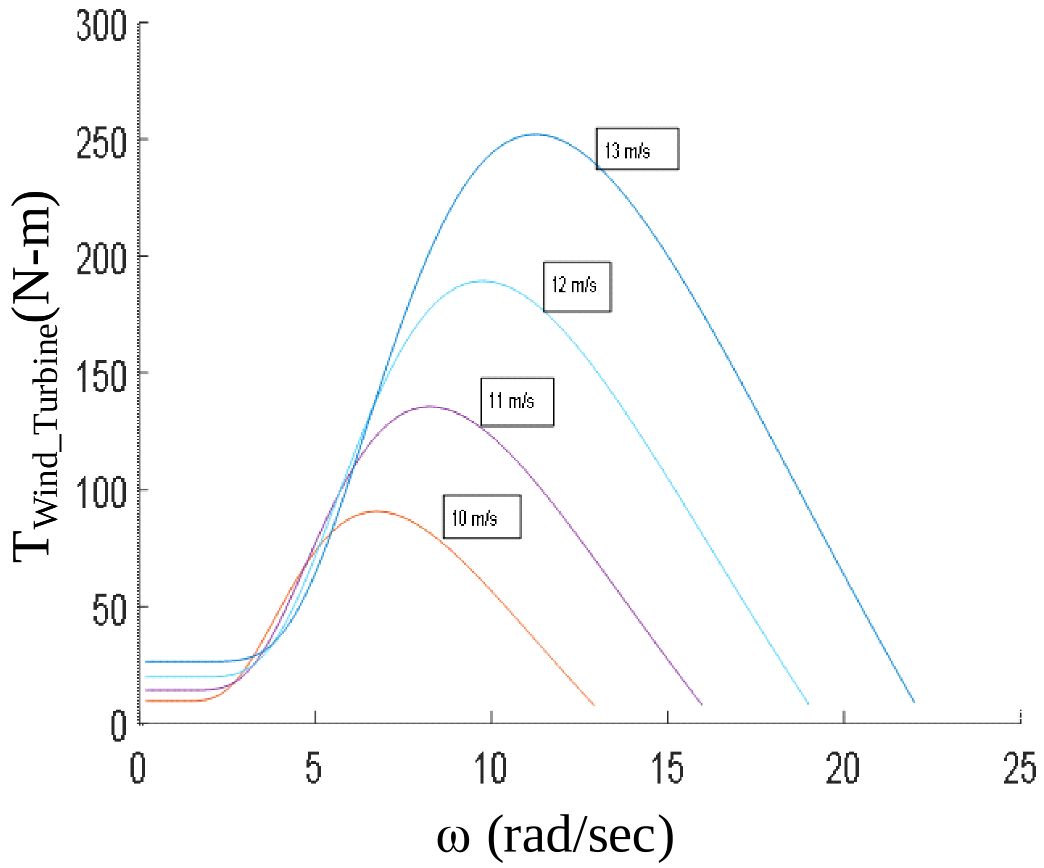

Figure 5.3 Turbine Torque-Speed Characteristics

The torque speed characteristics of wind turbine model on zero pitch angle and different wind speeds are shown in the figure 5.3. As the wind speed increases the turbine rotates at a higher speed and hence the power coefficient reaches its maximum value and at that moment the torque generated by wind turbine is also maximum. At turbine rotor speed of 14 rad/sec the generated torque by wind turbine is maximum on wind speed of 13 m/s.

5.2.2 Characteristic of Wind Emulator Using DC Motor

Figure 5.4 shows the characteristics of wind turbine emulated by using a separately excited dc motor. The field is kept constant and armature voltage control is implemented using a buck converter to get the desired characteristics.

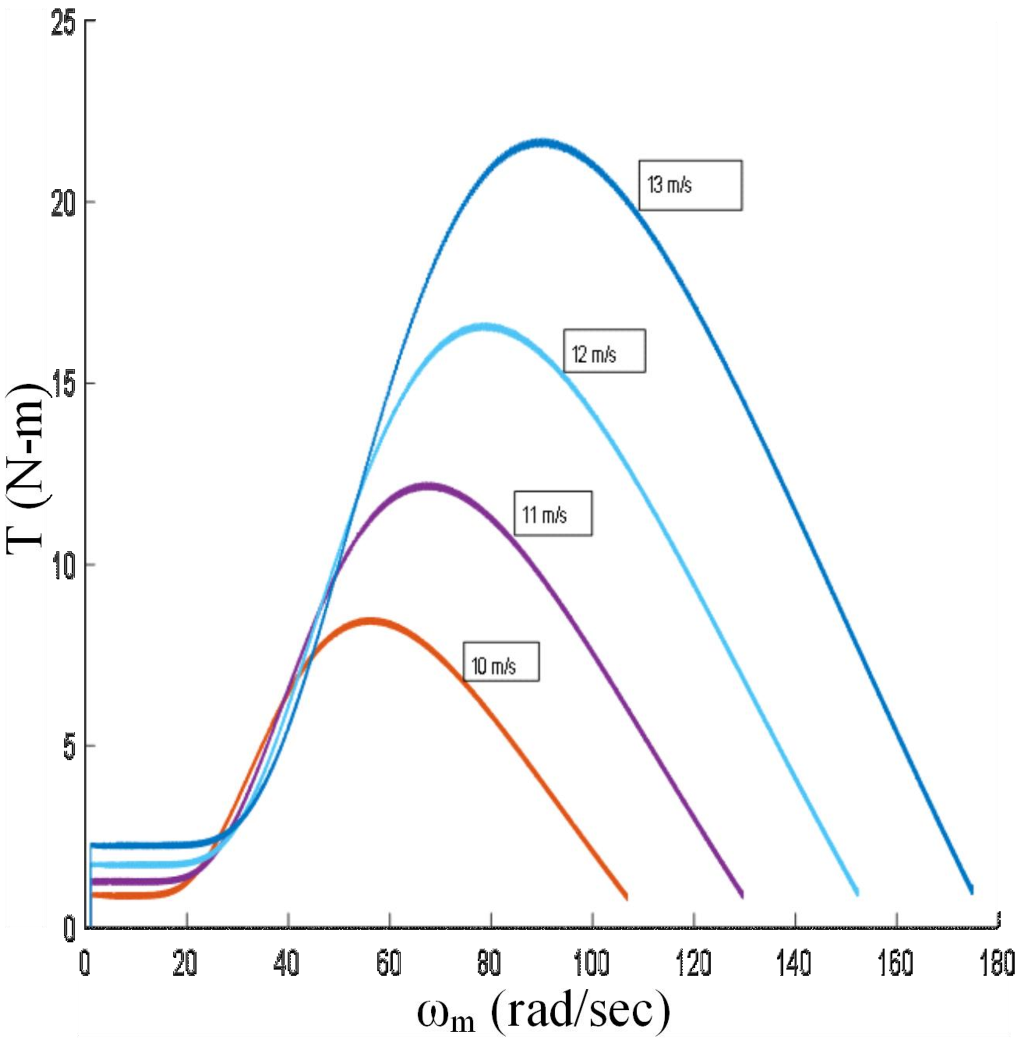

Figure 5.4 Characteristic of Wind Emulator Using DC Motor

The output torque from wind turbine is converted into reference torque by a gear ratio conversion and this reference torque's magnitude is reduced by adaptation of torque. By applying the torque constant, the reference torque is transformed into reference current and this reference current is compared with the actual armature current of dc motor. The error from the two currents is regulated using a PI regulator and the output of PI regulator is compared with a high frequency sawtooth signal which develops gate pulses for the buck converter and hence the speed of dc motor is controlled in such a way that the characteristics of wind turbine is emulated.

5.2.3 C_p – λ Characteristic of Emulator with Fixed Wind Speed

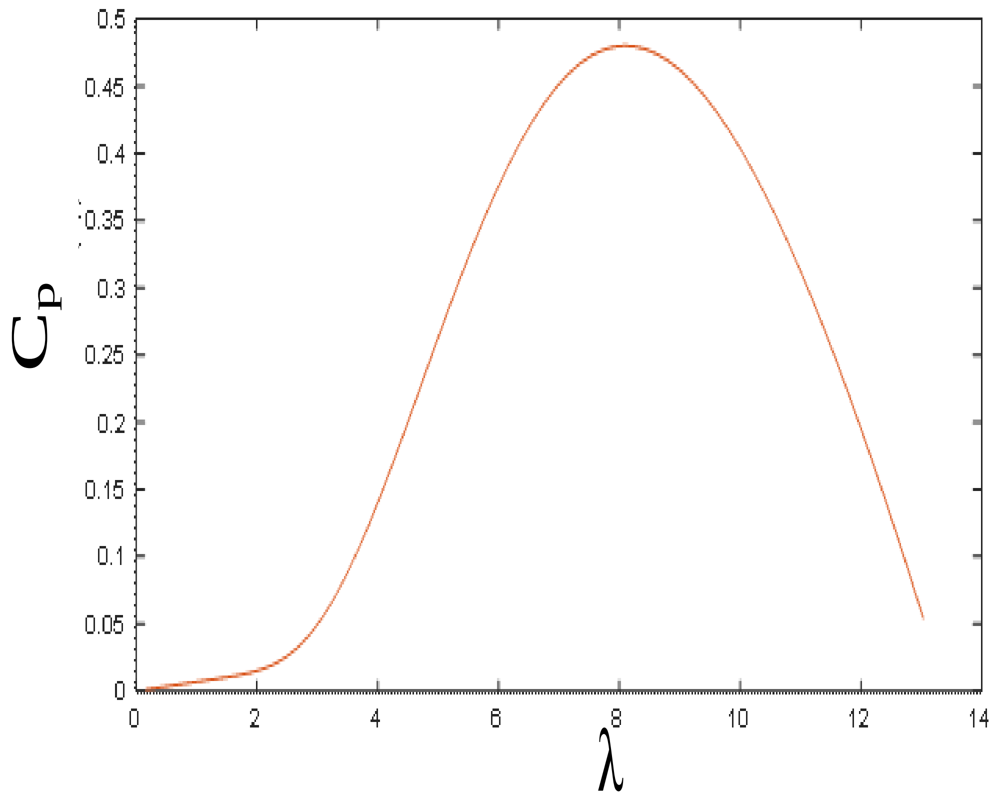

Figure 5.5 Power Coefficient Versus Lambda Curve

Figure 5.5 shows the variation of coefficient of power (C_p) and tip speed ratio (λ) on fixed wind speed. The value of power coefficient is less than 0.593 which satisfy the Betz limit and hence the turbine model is working satisfactorily. Power coefficient defies the amount of power which can be generated by a wind turbine from the wind and its high value is necessary to harness wind energy efficiently. At λ = 8, the value of power coefficient is maximum i.e. about 0.48. For harnessing maximum power from the wind, certain algorithms are used so that continuous power is generated at its peak which in this case is 0.48 that is about 48 percent of energy is extracted from wind.

5.2.4 Dynamic Performance of Emulator under Variable Wind Speed Condition

Figure 5.6 shows the characteristic change in performance parameters of wind emulator in variable wind speed conditions. The actual armature current tracks the reference armature current due to which the wind turbine characteristics are emulated satisfactorily.

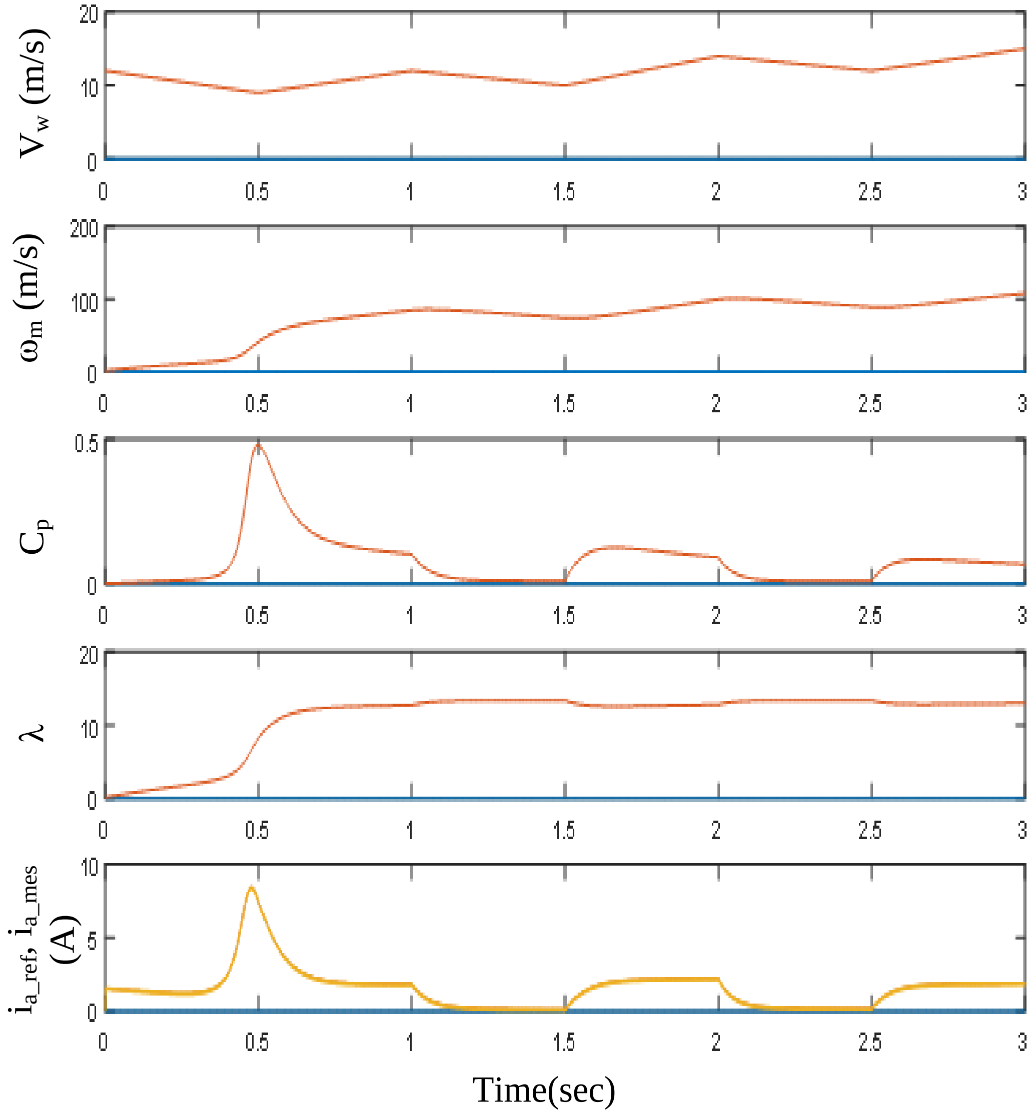

Figure 5.6 Performance Parameters a) wind profile; b) Motor Speed; c) Reference Armature current and Actual Reference Current; d) Power Coefficient; e) Tip Speed Ratio

Figure 5.6 shows the characteristic change in performance parameters of wind turbine emulator on condition of variable wind speed. When the wind emulator starts to operate i.e. from t=0 sec to t=0.5 sec, power coefficient and the armature current attains their peak value while motor speed and tip speed ratio increases. From t=1 sec to t=1.5 sec, the wind speed decreases from 12 m/s to 10 m/s, motor speed decreases and hence armature current also decreases with it but tip speed ratio increases in this case. From t=1.5 sec to t= 2 sec, the wind speed increases from 10 m/s to 14 m/s, motor speed and armature current increases in the system but tip speed ratio decreases. From t=2 sec to t=2.5 sec wind speed decreases and from t=2.5 sec to t=3 sec wind speed increases and the performance parameters behave as mentioned in above cases.

5.2.5 Modelling of Permanent Magnet Synchronous Generator (PMSG)

In recent years, power generation through wind has accelerated with the use of permanent magnet synchronous generators. [47] There are no copper losses in rotor circuit of PMSG and it gives high reliability and high efficiency in power generation as there is no need of external excitation. The cost and weight of wind turbines are reduced as the size of high power density PMSGs is pretty small. PMSG with power converters can operate at different wind speeds by adjusting the shaft speed optimally to extract maximum power.

Usually Park model is used as PMSG transient model [46]. The space vector theory gives the stator voltage equation in the form of

$$v_{sd} = - R_s i_{sd} - \frac{d\psi_{sd}}{dt} - \omega_e \psi_{sq} \qquad (5.2)$$

$$v_{sq} = - R_s i_{sq} - \frac{d\psi_{sq}}{dt} + \omega_e \psi_{sd} \qquad (5.3)$$

Where, R_s = resistance of stator winding

ω_e = generator electrical rotational speed

v_{sd} , v_{sq} = d and q-component of instant stator voltage

i_{sd} , i_{sq} = d and q-component of instant stator current

ψ_{sd} , ψ_{sq} = d and q-component of instant stator flux

if along the rotor flux position the d axis is aligned, the stator flux linkages will be given as follows:

$$\psi_{sd} = (L_{ls} + L_{dm}) i_{sd} + \psi_f \qquad (5.4)$$

$$\psi_{sq} = (L_{ls} + L_{qm})\, i_{sq} \tag{5.5}$$

Where, L_{ls} = stator winding leakage inductance

L_{dm} , L_{qm} = stator and rotor d and q-axis mutual inductances respectively.

ψ_f = permanent magnet produced flux linkage

The electromagnetic torque is given as

$$\tau_{em} = \rho\, (\psi_{sd}\, i_{sq} - \psi_{sq}\, i_{sd}) \tag{5.6}$$

$$\tau_{em} = \rho\, (\psi_f\, i_{sq} + (L_d - L_q)\, i_{sd}\, i_{sq}) \tag{5.7}$$

Where, ρ = number of pole pairs

$L_d = L_{ls} + L_{dm}$

$L_q = L_{ls} + L_{qm}$

In steady state condition equation 5.2 and 5.3 becomes

$$V_{sd} = -R_s\, I_{sd} - \omega_e\, L_q\, I_{sq} \tag{5.8}$$

$$V_{sq} = -R_s\, I_{sq} + \omega_e\, L_d\, I_{sd} + \omega_e\, \psi_f \tag{5.9}$$

For a direct driven multi pole PMSG the difference between d and q-axis mutual inductance is negligible and stator winding resistance is quite smaller as compared to synchronous reactance. So equations 5.6 and 5.7 reduced to

$$\tau_{em} = \rho\, \psi_f\, i_{sq} \tag{5.10}$$

and steady state d and q-axis currents from equations 5.8 and 5.9 are given by:

$$I_{sq} = -\frac{Vsd}{L_q\, \omega_e} \tag{5.11}$$

$$I_{sd} = \frac{(V_{sq} - \omega_e\, \psi_f)}{L_d\, \omega_e} \tag{5.12}$$

5.2.6 Dynamic Behaviour of PMSG Driven by Wind Emulator

When a permanent magnet synchronous generator is connected with wind turbine emulator, which in this case is separately excited dc motor, the build up of generator voltage, current and effect of load on PMSG is shown in figure 5.8. Torque and speed variations with stator currents are also shown. The PMSG used in simulation is of 6kW rating with armature resistance of 0.425 Ω, armature inductance of 8.4 mH and flux linkage established by magnets is 0.433 Vs. The separately excited dc motor which is being controlled as a wind turbine emulator is of 3.73 kW rating, with rated armature voltage of 240 V, field winding of 300 V and rated speed of 183.26 rad/sec.

5.2.6.1 Simulink Model of PMSG Driven by Wind Emulator

The Simulink model of wind turbine emulator driven PMSG is shown in figure 5.7. The torque output of emulator is given directly to PMSG so that it behaves as a prime mover to the generator. At the output of PMSG a specific resistive load is connected so that the PMSG can build the rated voltage and current.

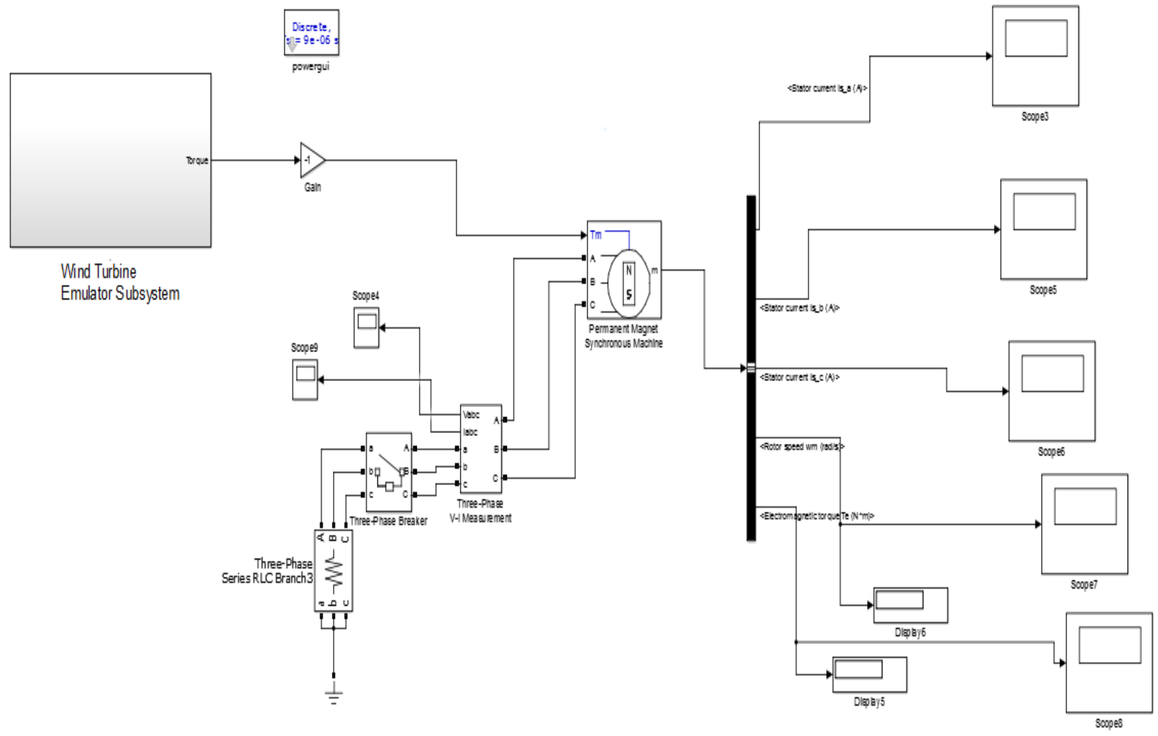

Figure 5.7 Simulink Model of PMSG Driven by Wind Emulator

Figure 5.7 shows the Simulink model and connection of wind turbine emulator with PMSG on a resistive three phase load. The voltage and current is build-up in PMSG according to the torque generated by dc machine which is being controlled to perform as a wind turbine emulator and hence dc motor is acting as a prime mover for PMSG.

5.2.6.2 Dynamic Performance of PMSG Driven by Wind Emulator

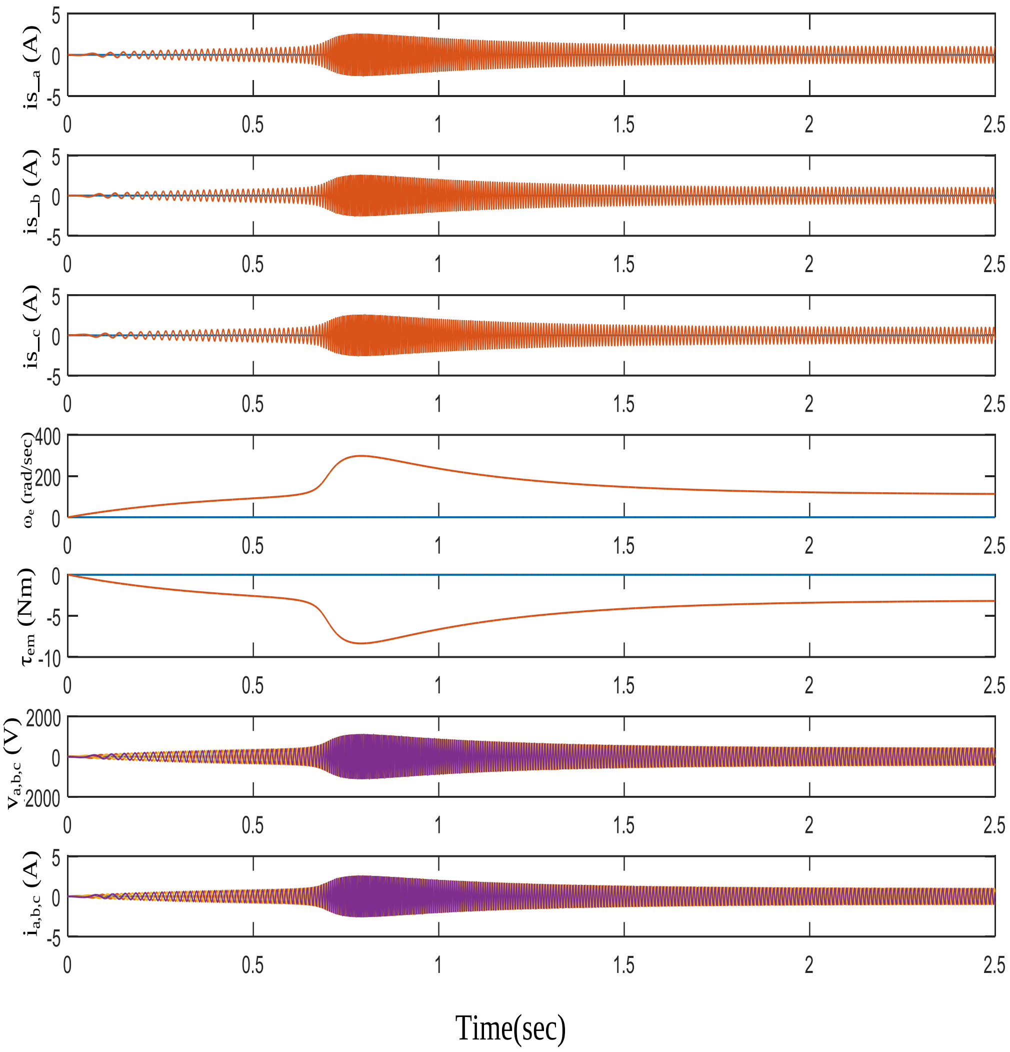

Figure 5.8 Performance Parameters of PMSG

From t=0 sec to t=0.75 sec the voltage and current starts to build up in a PMSG, the speed and torque increases. From t=0.75 to t=1 sec, the emulator reaches its peak value of torque and starts to decrease. The voltage and current of PMSG also increase to a maximum point and then starts to decrease to settle down on its rated value Speed of PMSG increases and starts to decrease. From t=1 sec to t=2.5 sec, the emulator torque settles down to a constant value and hence the current and voltage also settles down to the rated value of PMSG on a specified load. So the required voltage is build up in PMSG on a given constant specific load. The torque and speed also settles down within the rated range.

5.3 Conclusion

Wind turbine emulator model is developed and simulated in MATLAB using a separately excited dc motor and the dynamic behaviour of emulator under variable wind speed conditions is analysed while driving a PMSG. The results shown exactly resemble the wind turbine characteristics. Simulation model of wind turbine emulator works satisfactorily under variable wind speed and reference armature current of dc motor tracks actual armature current within limits. Rated voltage is build up in permanent magnet synchronous generator when connected with wind turbine emulator on a specified load.

CHAPTER-VI

CONCLUSION AND FUTURE SCOPE OF WORK

6.1 MAIN CONCLUSION

The main objective of the thesis was to simulate the characteristics of wind turbine using a separately excited dc motor in Matlab/Simulink environment. The research work developed a wind turbine emulator which is dependent on wind speed and other performance parameters of wind turbine. Chapter 3 discussed about the wind energy conversion system and wind turbines in detail. The steady state and dynamic characteristic of turbine are emulated using dc motor and torque-speed and power-speed behaviour of wind turbine model are studied. The controller and controlling techniques with the machine used in simulation are discussed. A buck converter is used to control the armature voltage of dc motor and a PI regulator is used to regulate and to minimise the current error. This wind turbine emulator can be used as a tool to encounter unpredictability of wind so that continuous supply of energy can be achieved in wind energy conversion system. This wind emulator was connected with a permanent magnet synchronous generator as a standalone system and rated voltage is build up on a specified load.

6.2 FUTURE SCOPE OF RESEARCH WORK

DC motor is used in the current scheme of research work. Other AC machines like induction motor, synchronous motor or servo motor can be used to build a wind turbine emulator with different controlling schemes. A hardware model of wind turbine emulator may be developed using a real interface card like d- space or with some microcontroller.

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APPENDIX

Wind Turbine Parameters	
Rated Turbine Power	10 kW
Air Density	1.225 Kg/m^3
Turbine Radius	3 m
Turbine Inertia	0.042 Kgm^2
Rated Speed	24 rad/sec
Gear Ratio	7.6

DC Motor Parameters	
Rated Power	3.73 kW
Field Voltage	300 V
Armature Voltage	240 V
Rated Speed	183.26 rad/sec
Armature Resistance	2.581 Ω
Armature Inductance	0.028 H
Field Resistance	281.3 Ω
Field Inductance	156 H
Field Armature Mutual Inductance	0.9483 H
Total Inertia	0.02215 Kgm^2
Viscous Friction Coefficient	0.002953 Nms
Coulomb Friction Torque	0.5161 N-m

PMSG PARAMETERS	
Rated Power	6 kW
Stator Resistance	0.425 Ω
Armature Inductance	8.4 mH
Flux Linkage	0.433
Inertia	0.01197 Kg m^2
Viscous Damping	0.001189 Nms
Pole Pairs	4

Proportional Integral Controller Parameters	
K_P	9.01
K_I	1.96

Sawtooth Carrier Wave Frequency	2 kHz