PERFORMANCE IMPROVEMENT OF PERMANENT MAGNET SYNCHRONOUS GENERATOR BASED WIND ENERGY CONVERSION SYSTEM

A DISSERTATION

Submitted in the partial fulfillment of the

Requirement for the award of the degree

of

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in

ELECTRICAL ENGINEERING

(With Specialization in Electric Drives & Power Electronics)

by

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Declaration

I declare that the work presented in this dissertation with title, "**Performance Improvement of PMSG based Wind Energy Conversion System**", towards the fulfilment of the requirements for award of the degree of **Master of Technology** in **Electric Drives and Power Electronics**, submitted to the **Department of Electrical Engineering**, **Indian Institute of Technology-Roorkee**, India, is an authentic record of my own work carried out during the period from **June 2015 to May 2016** under the guidance of **Dr. Sharmili Das**, Assistant Professor, Department of Electrical Engineering, Indian Institute of Technology, Roorkee.

The matter presented in this dissertation has not been submitted by me for the award of any other degree of this or any other institute.

Date:

Place: Roorkee **(Rohith Sreenivas)**

This is to certify that the statement made by the candidate in the declaration is correct to the best of my knowledge and belief.

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Abstract

Earlier, the wind energy conversion systems were implemented using squirrel cage induction generators and are operated at fixed speed to get the output voltage at a fixed frequency. But with the advancement in power electronics, advanced control strategies and modified circuit topologies, wind energy systems are now implemented using other machines like Doubly Fed Induction Generators (DFIG) and Permanent Magnet Synchronous Generators (PMSG) and also are operated at variable speeds. Nowadays DFIG are used for majority of the wind energy systems. But the PMSG based wind energy conversion systems has certain superior qualities when compared to DFIG based wind energy conversion systems.

In this dissertation, it will consider its work on modeling of PMSG based wind energy conversion system and the possible changes which can be implemented to improve the performance of the system. The wind energy system is designed for variable speed operation. MPPT technique is used so that maximum possible power can be absorbed from the system at all operating conditions. A study is done on improving the performance of the system so that the system will be able to provide the output voltage at a fixed frequency meeting the required power factor and dealing with the synchronizing issues so that all the grid requirements are met. To verify the theoretical results, simulation results are carried out.

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List of Acronym

PMSG	Permanent Magnet Synchronous System
DFIG	Doubly Fed Induction Generator
SCIG	Squirrel Cage Induction Generator
WECS	Wind Energy Conversion System
MPPT	Maximum Power Point Tracking
PWM	Pulse Width Modulation
PI	Proportional and Integral
THD	Total Harmonic Distortion

Chapter 1

Introduction

1.1 Overview

As a renewable energy resource, wind energy systems always had a prominent role in energy production. Compared to other non-renewable energy sources like fossil fuel and nuclear power generation system, wind energy systems are environmentally safe, clean and cost competitive. Compared to other renewable energy sources, wind energy systems require a little maintenance, low installation cost and also better efficiency. Currently, most popular wind energy systems are variable speed wind energy conversion systems. Mainly three type of machines are used for wind energy systems which are Squirrel cage induction generators (SCIG), Doubly fed induction generators (DFIG) and permanent magnet synchronous generators (PMSG). Compared to the other two generators, PMSG has certain superior qualities. One of the main advantage of PMSG is that they can be connected directly to the turbine without the use of gear drives. The absence of gear drives improves the efficiency of the system by a reasonable amount and also reduces the maintenance issues in the system. Similarly, they don't require external excitation. Thus it can reduce the cost, size, losses and maintenance requirements.

A complete wind energy conversion system is modelled and connected to a three phase grid. MPPT technique is implemented in the system and is included in the control algorithm. The complete wind energy conversion systems can be divided into many parts which constitutes a wind turbine which absorbs the wind energy, a PMSG which converts the absorbed energy into electrical energy, a PWM controlled rectifier at the generator side where the MPPT scheme is employed, a DC link and a PWM controlled inverter at the grid side which controls the DC link voltage and also controls the power factor of the power output. The MPPT scheme is employed by making the machine operate at a required optimum speed by controlling the electromagnetic torque of the machine, which is directly proportional to the q axis current and thus can be controlled by controlling the same. This control is implemented in the generator side controller. Along with the q axis control, d axis current is also implemented by which certain advantages can be made. As d axis current is not affecting the torque and has no role in it, by reducing it and making it to zero, we can reduce the copper loss. Also by controlling d axis current, we can implement flux weakening operation mode. In the grid side inverter, mainly two objectives are there which are controlling the dc link voltage to a fixed value and to maintain the power factor at a required value. In the starting chapter, the history of the wind energy conversion systems and the advantages of PMSG based wind energy conversion systems over other types are discussed. Afterwards, in chapter 2, the models of PMSG and the wind energy system as a whole is shown. The control methods are discussed in chapter 3. The results and conclusion forms the chapters 4 and 5.

1.2 History

The first of its kind horizontal axis wind turbine may have been in use from early 12th century. At that time these systems were used mainly for agricultural purposes and due to the growth in agricultural sector, the need for more efficient systems increased. But at these times, there was no regulation for the operating speed of the turbine and were only regulated by simple mechanical breaking systems employed which is used only in times of storms or such emergency situations. These systems were mostly standalone systems which will be used for a particular small scale purpose.

But as electric era started in the early 20th century, many companies started providing so many electrical appliances which made the world to dream of an electric powered world. Many of the machines depended on direct current at that time and so the power generators designed at that time were more focused on direct current generation. Several dc wind generators were developed at that time [2]**.** and they were all working at variable speed. But later, as the AC gain its importance, the demand for ac supply also increased. The grid system also came into existence and so there arise a need to connect all the power generation systems to connect to a single grid. But here, as it is to be connected to a common grid, the frequency of all the supplied power has to be same. Thus variable speed wind energy generation lost its importance and there arise a need for a constant frequency power generation. This is made possible by using mechanical speed regulators. By using pitch control and yaw control, it is able to operate the wind turbine at a fixed speed and thereby generating the power at a fixed frequency. But in this case, when the wind speed is high, we cannot utilize the high wind power obtained as it will increase the rotation speed and thus the frequency. Thus we have change the pitch angle to a value such that it will not absorb the available maximum power so as to operate at a constant speed. Thus the disadvantage seems easily visible as the system is not able to absorb maximum available wind power at every wind speed. At that time, most wind energy conversion systems involve squirrel cage induction generators. They were cost efficient, small in size and easy to implement when compared to other machine based wind energy systems. As the wind speeds are normally less, the rotation speed has to be increased to a higher value so that the generator can operate in its efficient speed. This was made possible using gear drives. Even though it results in slight decrease in efficiency due to the additional mechanical losses of the gear drive, net efficiency increases due to the generator operating at its efficient speed.

The variable speed wind systems had many advantages compared to fixed speed operation and the main disadvantage they possessed was their inability to provide power at fixed frequency. But due to the advancements in power electronics, by using inverters and converters, we can change the frequency of the generated voltage to any required value. Thus the only disadvantages possessed by the variable speed wind systems are now eradicated. Thus after the advancements in power electronics field, the demand for variable speed wind systems increased. Mainly three type of machines were used for this systems which are squirrel cage induction generators, doubly fed induction generators and permanent magnet synchronous generators. Initially, squirrel cage induction generators were mainly used. But the doubly fed induction generators were having much larger advantages when compared with squirrel cage induction generators. In doubly fed generators, the inverter is connected only in the stator side where only a small part of generated power is flowing. Thus a small rated inverter is only required when compared with induction generators where a full rated inverter is required. Thus due to the advantages of the DFIG system, it became so popular so that nowadays most of the new wind turbines are using DFIG.

But recently, a new competitor for DFIG appeared in the industry which is the PMSG based wind systems. They use the permanent magnet synchronous generator which has many superior qualities compared to doubly fed induction generators and are lacking the disadvantages of squirrel cage induction generators. But still the PMSG is also having some issues which need to be dealt with, so as to make it the best alternative for DFIG. Many researches are going on in this field involving both DFIG based wind energy conversion systems and PMSG based wind energy conversion systems.

1.3 Objective of work

This work contains the simulation of wind energy conversion system based on PMSG which aims to absorb the wind energy at maximum efficiency possible. Main objectives of this work are as follows:

a) Model a complete wind energy conversion system which includes the wind turbine, generator, back to back converter and the grid
b) Analyze different control strategies which can be used to maximize the power absorption.
c) Design a system which can provide the active power at the grid required reactive power.

1.4 Organization of Thesis

This thesis mainly consists of five chapters. Main contents of each chapter are as given below:

The chapter1 includes an introduction and history of the wind energy conversion system and also the objective of work

The chapter 2 includes the literature survey

The chapter 3 discusses about different types of wind energy conversion system and a detailed comparison between each of them

The chapter 4 includes a model of PMSG machine and the mechanical model of wind turbine and their details

The chapter 5 deals with the control topologies which can be implemented in the system both on the generator side and the grid side

The chapter 6 includes the simulation and the obtained results in the form of waveforms

The chapter 6 is the last chapter includes the conclusion obtained from the results and also discusses about the future scope of the topic

Chapter 2

Literature Review

Today, the most important problem in wind energy field is maximum power absorption [1- 4]. All major literatures published in this field will be considering about this issue. A large amount of effort is made to implement the most efficient way of maximum power extraction.

H.Li [2] discusses about the advaatages of different types of wind energy systems and compare between their advantages and disadvanatages. Initially the fixed speed concept was discussed and then, stating its disadvantages, moving on to various kinds of variable speed wind energy conversion systems. Compared to fixed speed concept, variable speed systems are always more economic and efficient. And the two main machines which can be used for variable speed operation are DFIG and PMSG as induction generators are much less efficient compared to them.

Rajveer Mittal et al.[5] dicusses about the major issues seen in the wind energy systems other than difficulty to absorb maximum power. A comparison between horizontal axis wind turbine and vertical axis wind turbine is done. Eventhough the vertical axis wind turbine requires large installation cost as it need lage structures, it is still considered efficient for large power operation. The wind capture capacity of vertical axis wind turbines are comparitively less. Thus the horizontal axis turbines are preferrred. There are also certain grid related issues in wind energy system like voltage disturbances, synchronisation issues, harmonics, poor grid stability, low frequency operation issues and impact of low power factor.

Henk Polinder et al.[6]**.** dicuss the advantages of direct driven and indirect driven wind turbines. Direct driven wind turbine doesn’t uses gear drives and they have a large advantage of reducing the mechanical losses. But as wind speeds are comparitively not high, the turbine speed usually is low and needs to step up into a high value so as to opreate the generator at its higher efficiency operating point. Only in PMSG based WECS, it can operate at low speeds. PMSG are compact due to the absence of windings and so the number of poles can be increased to a larger number. By increasing the number of poles to a larger value, the possibility of designing a low speed PMSG is feasible.

E. Spooner[7] discusses about the advantages of PMSG based WECS as PMSG doesn't require supply of reactive power for the excitation as it already have a permanent magnet.

Tayeb Bukhari et al. [8] discusses about various proposed methods of frequency control methods proposed in the field of DFIG based WECS. The first two methods being pitch control and gear ratio control. By designing a system with automatic pitch control, a system which can always run at a fixed speed can be formed thus making the frequency constant. Similarly, in gear ratio control, when wind speed is decreasing, the gear ratio is changed to a different configuration so that the generator will operate at a fixed speed and thus making the frequency constant. Third scheme proposed is by using converters. Last one obviously makes the perfect choice as it does not involve any mechanical control and thus more efficient and effective.

R. Pena et al.[9] proposes a method of using back to back converter with vector control employed in DFIG based WECS which makes it possible to control the active and reactive power independently and also to acquire maximum power tracking. In DFIG, the control is implemented in rotor side. Only a small fraction of power is flowing through the rotor side and so only a low rated converter is required. A disadvantage also exists as the whole power is not flowing through the converter. Controlling of active and reactive power is not so effective in this case.

Dong-Min Miao et al [10] proposes a method of flux weakening in PMSG based WECS. Normally flux weakening in motors are only discussed to operate them at more than rated speed. It is proposed to use flux weakening method in PMSG to increase the range of operating speed. The flux weakening or strengthening can be achieved by controlling the d axis current in a rectifier using vector control. By giving a positive d axis current, flux strengthening can be done and by negative d axis current, flux weakening can be implemented. But care should be taken not to completely demagnetize while flux weakening and also not to saturate while field strengthening.

Monica Chinchilla [11] discussed about using a back to back converter for variable speed PMSG system which can control active and reactive power independently. Similar topologies are proposed [12][13][14][15] which all involves the back to back converter and using of different techniques like space vector modulation, pulse width modulation etc. Similarly, many methods of implementing MPPT techniques, which is done to absorb maximum power, are proposed where some of them involves MPPT algorithms and look up tables to be used and other uses calculation of optimum torque value which can be applied so as to absorb maximum power from the system.

Chapter 3

Types of WECS

3.1 Introduction

Wind energy is one of the easiest available form of energy which is also a renewable and clean form of energy. These reasons gave much popularity for the wind energy in the field of energy. But the main problem of any energy resource is to get the continuous flow of energy at a reasonable efficiency. To achieve this, many researches in this field was done in different periods of time. As with the advancement time, the technologies also started to grow and thus the machines used for the same started changing. Thus there were different types of wind energy conversion systems each based on a specific electrical machine. Mainly three types of WECS are popular which are the SCIG based WECS, DFIG based WECS and the PMSG based WECS. In this chapter, the comparison between these different types of WECS are done and the advantages and disadvantages of each types are detailed and compared.

3.2 Comparison between different types of WECS

Until the last two decades, the main choice for wind turbine were squirrel cage induction generator. But thereafter due to the great advancements in power electronics field, another choice became popular which is the doubly fed induction generators. Recently a new option also came in this field which is the PMSG. In older times when fixed speed wind turbines were used, the SCIG seems perfect for the system as they were compact in size making it easy to install, less costly and were less complex to handle. Also they don't have slip ring issues and they do not require external excitation unlike synchronous generators. But they were requiring reactive power from the grid to provide excitation for them and that was a disadvantage. But still this was a good choice for fixed speed wind systems compared to using synchronous generators for the same purpose. Synchronous generators were large in size and requires external excitation which together make it a poor choice for a turbine system which has to be mounted on a tall structure.

But as the variable speed systems were introduced for wind systems using power electronic converters, SCIG started to fade away from the market. Because if we have to control the SCIG using power electronic converters, we have to use a large converter as the whole power is flowing through it. Thus the control action become troublesome and costly. If DFIG is used for the same system, then the converter is used only at the rotor side and so a low rated converter is only needed as a small fraction of power will only flow through the converter. Thus smaller size converter can be used thus making it cost efficient. But as the full power is not flowing through the converter, the controlling action is not that effective as in the induction generator. Similarly, by using a small rated converter, an additional advantage is there which is the reduction of THD introduced by the converter. Smaller the converter, lesser the THD introduced by the converter into the grid which largely affects the power quality. So the converter has both the advantages and disadvantages. So the best way possible is to design and use a converter which has very less THD issues.

Later, researches were carried on the third alternative which is the PMSG based wind turbines. Main attracting features of the PMSG system are its compact size and less complexity. PMSG machines uses permanent magnets. A small size magnet can produce the same magnetic field produced by larger field findings which requires larger space thus making the whole system bigger. This feature makes the PMSG based WECS easy to install in a tall structure and thus making the structure requiring less strong foundation structures compared to DFIG based WECS. Another important feature of the PMSG based system is that they don't require reactive power supply from system which was a problem in SCIG and DFIG based WECS. But in PMSG based WECS, a full rated power electronic converter is required which makes the system not only costlier but also introducing larger THD issues in the grid. But absence of gear drives causes an increase in efficiency in the system compared to DFIG based WECS.

3.3 Advantages of PMSG based WECS

Before 2003, the SCIG based fixed speed wind turbine were completely ruling the wind turbine industry and after that DFIG entered into the market and almost 85% of the market was using the DFIG based WECS. But recently, PMSG based WECS has been getting more attraction because of some attracting features of the PMSG and also due to the technical disadvantages of DFIG. Generally, permanent magnet machines have larger air gaps compared to other machines with field windings. Thus flux linkages are less in the PMSG based systems and thus for a required power rating, a low speed PMSG can be developed with lesser size compared to a DFIG machine. An additional advantage here is that, as it can operate at low speed, the requirement of gear drives can be neglected. This not only reduces the cost but also increases the efficiency. For direct driven generators, generally, to increase efficiency, they are designed with large diameters and with a decreased small pitch. But for a generator with field winding, increasing the pole pitch is a difficult task and not easily possible. But in permanent magnet machines, we can easily make it possible as we are using magnets and thus the number of poles can be increased to a large value and thus reducing the pole pitch to a much smaller value. By the use of permanent magnets, we can achieve a high torque density and also make the excitation losses equates to zero in the machine. In recent times, the permanent magnets are becoming cheaper in the market and thus it makes it less costly for the PMSG which lessens the existing disadvantages of the PMSG based WECS. Also by the use of high energy permanent magnets, the volume of the magnets can also be reduced thus reducing the size of the machine. These advantages are making the PMSG based WECS a popular choice for wind turbines especially in the field of offshore wind turbines. Along with this, due to the absence of field winding, efficiency is increased as heat dissipation is reduced. By the application of high energy permanent magnet materials like neodymium-iron-boron, the volume and thereby the cost of machine can be highly reduced. Thus, advantages offered by PMSGs are simple rotor design without field winding. The absence of field windings also results in higher efficiency since heat dissipation is avoided. PMSG is gaining a lot of attention for WECS due to compact size, high reliability higher power to weight ratio, reduced losses and robustness.

Also, when compared with DFIG based WECS, PMSG based WECS is using a full power rated power converter by which a full power controllability is achieved. By this, we are easily able to control the power flow and thereby it becomes more efficient to provide the active and reactive power of required rating. Similarly, during fault condition, it will be easy to handle the fault in PMSG based WECS as full power is flowing through the converter. Fault ride through operation is much difficult in other types of WECS. Further, PMSG operates at higher efficiency and better power factor than its counterparts and the results are even better when it functions as a direct driven generator.

3.4 Performance Issues prevailing in PMSG based WECS

PMSG based WECS has many advantages but that doesn’t make it free of disadvantages. PMSG based WECS has got certain issues which need to be taken care of. The system is effected by serious problems during fault conditions such as over speeding of the generator speed and the capacitor voltage to increase or decrease beyond the limits. So abler control of the generator and the power electronic converters for the achieving of the fault ride through condition is required. The system must be also capable of producing maximum power during normal operation that also at the grid required power factor. Grid synchronization issues also will be existing during the starting which also need to be dealt with. There are also certain disadvantages due to the using of a full rated converter because of the large amount of THD introduced by the converters. This also has to be regulated under the limits for the satisfactory operation of the system.

Chapter 4

Mathematical modeling of WECS

4.1 Introduction

In this chapter the modeling of the whole WECS is discussed. The wind energy conversion system can be divided into different sub parts. The main parts include the wind turbine which is the mechanical part, then the generator, the converter and the grid. The last three parts whole together make the electrical circuit. The modelling of the main parts which is the wind turbine and the generator is discussed in detail in this section.

4.2 Mathematical model of Wind Turbine

The wind turbine is composed of several parts to achieve energy conversion from kinetic to the required electrical energy. The Blades mounted on the rotor hub converts the wind kinetic energy to mechanical energy. The rotor hub is installed on the main shaft. It is also known as the low speed shaft. The drive train consists of shafts, bearings, and gearbox. The mechanical energy is transmitted through this drive train to the generator, which converts mechanical energy into electric energy. A power converter is placed along with this system. This converter converts the generated power from the generator to the grid. An important parameter for controlling the lift force of the blade is the angle of attack. It is the angle between the direction of the wind speed V_w and the cord line of the blade. The torque is zero when the angle of attack is made to zero as the lift force is zero. In olden times, these angles are adjusted to adjust the speed to make the generator operate at fixed speed. Later when new age devices came to exist, this technology was considered outdated. Making the angle of attack equal to zero results in stopping of the wind turbine. This process is called parking of the turbine. This is used for braking of the generator in times of abnormality in wind speed and also in times of repair or maintenance. The power produced by an air mass flowing at speed V_w through an area A can be calculated by

$$P_w = 0.5\rho A v_w^3 \qquad (1)$$

where ρ is the air density in kg/m3, A, the sweep area in m^2, and V_w the wind speed in m/s. The air density p is a function of air pressure and air temperature. At normal conditions, that is at sea level and a temperature of 15°C, the density of air is approximately 1.2 kg/m3. The kinetic energy or the wind energy captured by the turbine blades and converted into mechanical power is calculated according to the equation

$$P_w = 0.5\rho A v_w^3 C_p \qquad (2)$$

In this equation, *Cp* is the coefficient of power of the blade. This coefficient of power cannot be any value and it has its theoretical maximum value equal to 0.59 which is according to the Betz limit. With today's advanced technology, the maximum value of coefficient of power varies from 0.2 to 0.5, which depends on rotational speed and number of blades. From the above equation, the torque which can be produced by the system can be found according to the equation

$$Tm = 0.5\Pi\rho C_p(\lambda)R^2 v_w^3/\omega_r \qquad (3)$$

where R is the turbine radius, V_w is the wind speed, ω is the angular speed of the turbine. λ, which implies the tip speed ratio has got some significance in the wind energy system. It is the ratio of blade tip speed to the velocity of the incoming wind. It is given by the equation

$$\lambda = \omega_r R/V_w \qquad (4)$$

Calculation of C_p can be done a look up table of turbine power coefficient which is specific for each wind turbine. It can also have calculated from the equation given below which is,

$$C_p = 0.5176[116/\lambda_i - 0.4\beta - 5]e^{-21/\lambda i} + 0.006795\lambda_i \qquad (5)$$

Where

$$\lambda_i = [1/(\lambda + 0.08\beta) - 0.035/(\beta^3+1)]^{-1} \qquad (6)$$

From these equations, if a graph is plotted, one thing can be observed. For a specific wind turbine, for each wind velocity, there exists a certain point of wind generation speed for which, the value of C_p is at its maximum. This also implies, as per the equations, that for each wind velocity, there exists a certain point of generator rotational speed for which maximum power can be generated. This can be observed from the figure (**Figure *1***),

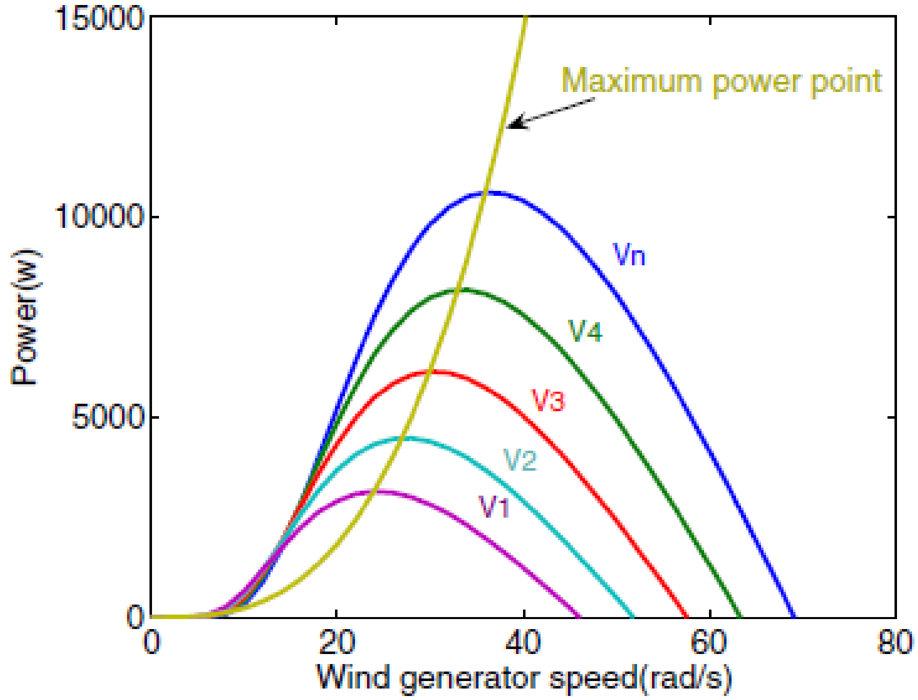

Figure 1 Wind generator power curves at various wind speed

So if we are able to operate the system at these particular speeds, then we can extract maximum power always from the system and that is the basic idea for maximum power point tracking. In the figure (**Figure *1***), it shows the schematic diagram of wind turbine simulated using Matlab/ Simulink. The equations mentioned above are used for the modeling of the system. Here, wind speed, generator speed and pitch angle is given as the inputs and we are obtaining mechanical torque developed as the output. Initially, the torque to speed ratio (TSR) is calculated from the rotational speed and the wind velocity. From this, using the pitch angle and the tip speed ratio, the coefficient of power is calculated using the above equation. Using the obtained values, the torque and power generated can be calculated. This output can be fed to the PMSG machine either directly or after stepping up the speed using gear mechanism. Here as PMSG based WECS is used, direct driven machine is considered as PMSG is efficient even at low speed and so can be operated without the use of gear. Thus the gear drive can be eliminated in this type of wind turbines.

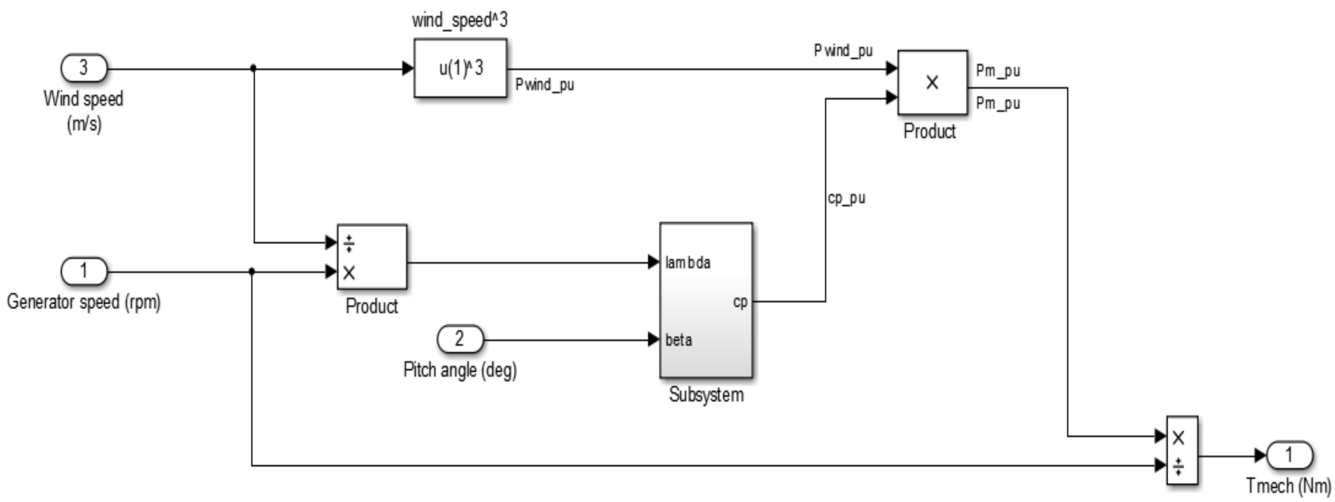

Figure 2 Wind turbine modeled with Simulink

4.3 PMSG Model

The PMSG has been considered as a system in which the electricity is produced from the mechanical energy obtained, which in this case, is the wind energy. The dynamic model of the PMSG is derived from the two phase synchronous reference frame, in which the abc synchronous reference frame, which is making an angle 120° with each other, is converted into dq reference frame in which q and d vectors are making an angle 90° with each other. The q-axis is 90° ahead of the d-axis with respect to the direction of rotation. By utilizing a phase locked loop (PLL), the synchronization between the *d-q* rotating reference frame and the abc-three phase frame is maintained. For the mathematical modeling of PMSG for power system and converter system analysis, usually certain assumptions are to be made which are mentioned as follows: stator windings placed in the air gap are considered to be sinusoidal placed as far as the mutual effect with the rotor is considered; the rotor inductance is considered to be constant at any time instant and is not varying with respect to the stator slots; the effects of saturation and hysteresis are neglected and so is not considered here; the stator windings are assumed to be symmetrical; also it is considered that the damper windings are absent; resistance of all the windings are considered to be constant which makes the power loss constant; similarly, any capacitance is not considered or they are simply neglected. The state equations for the mathematical model of the system in the synchronous reference frame is given below:

$$di/dt= (1/L_{ds}+L_{ls})(-R_s i_d + \omega_e(L_{qs} + L_{ls})i_q +u_d) \quad (7)$$

$$dq/dt= (1/L_{qs}+L_{ls})(-R_s i_q - \omega_e[(L_{ds} + L_{ls})i_d +\psi_f] + u_q) \quad (8)$$

here, d and q given as subscripts represent that the quantity given is represented in the d-q reference frame and that they are transformed from the abc form to d-q synchronous reference frame. Also the s letter as subscript refers to the stator. Stator resistance is represented by R, *Ld* and *Lq* are the inductances of the generator in the d and q axis. L_{ld} and L_{lq} are the leakage inductances [H] of the generator on the *d* and *q* axis, ψ is the permanent magnetic flux [Wb] and *We* is the electrical rotating speed [rad/s] of the generator, defined by

$$\omega_e= p\omega_g \quad (9)$$

where *p* is the number of pole pairs of the generator. From this equation, the values of current can be calculated by solving the equation. Inorder to complete the modeling of PMSG, the electromagnetic torque needs to be calculated. As the current values are obtained from the above equation, now the electromagnetic torque generated can be found out using the equation below,

$$T_e= 1.5p((Lds-Lls)i_d i_q + i_q\psi_f) \quad (10)$$

The complete PMSG model modeled in Matlab/Simulink is shown in the figure (**Figure *4***). Here it is considered that the machine is not connected to a grid and thus terminated across a load. The mechanical torque is given as input which is obtained from the wind turbine which is already modeled. From mechanical torque(T_{mech}) and the electromagnetic torque(T_e), the rotational speed ω_r is calculated which is shown in the figure(**Figure *3***). By obtaining the rotational speed (ω_r), the current calculation can now be done using the required equations which are already mentioned above. From the current equations, the electromagnetic torque is calculated. As it is considered that the machine is considered across a load, the voltage generated at the output is calculated from the d and q axis currents and the load parameter values.

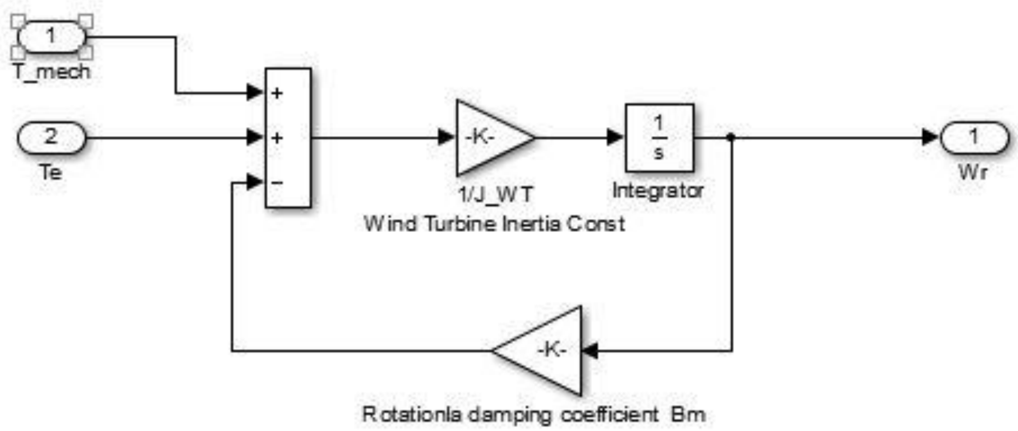

Figure 3 Calculation of rotational speed

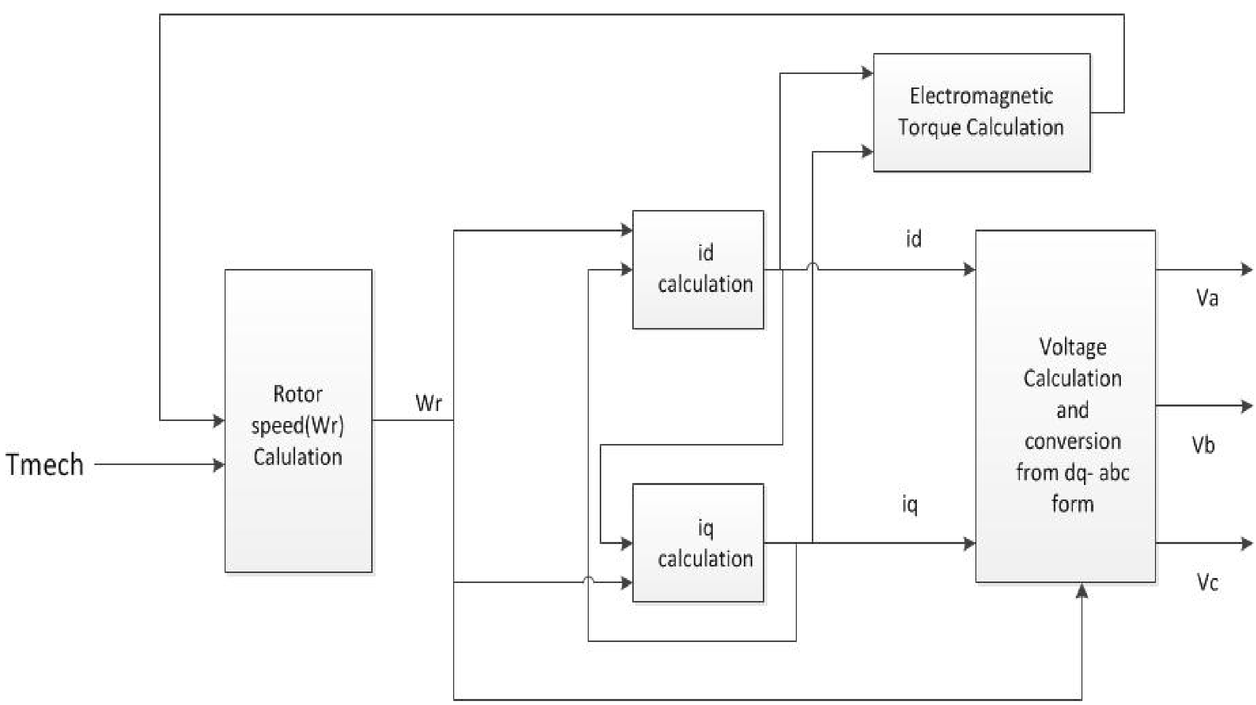

Figure 4 PMSG modeled with Simulink

Chapter 5

Control of WECS

5.1 Introduction

Here we are considering a multipole PMSG based variable speed wind turbine. As we are using a low speed PMSG, the shaft is directly connected to the generator thus making it a direct driven wind speed system. Thus there is no requirement of gear box in the system thus reducing the losses in the system. The whole wind energy system consists of many components which are a) Wind turbine b) PMSG machine c) controlled rectifier d) a DC- link capacitor e) Controlled inverter f) PWM module on both side for controlling both inverter and converter g) an RC filter and d) the grid. This whole system can thus be divided into two parts, the generator side and the grid side. The generator side consists of the wind turbine, the generator and the controlled rectifier and the PWM module which is connected to the DC link. The grid side consists of the inverter and the PWM module, filter and the grid. These two parts are joined by the dc link. The whole system is simplified and shown in the figure below where the PWM module and the vector controlling is not shown(**Figure *5***)

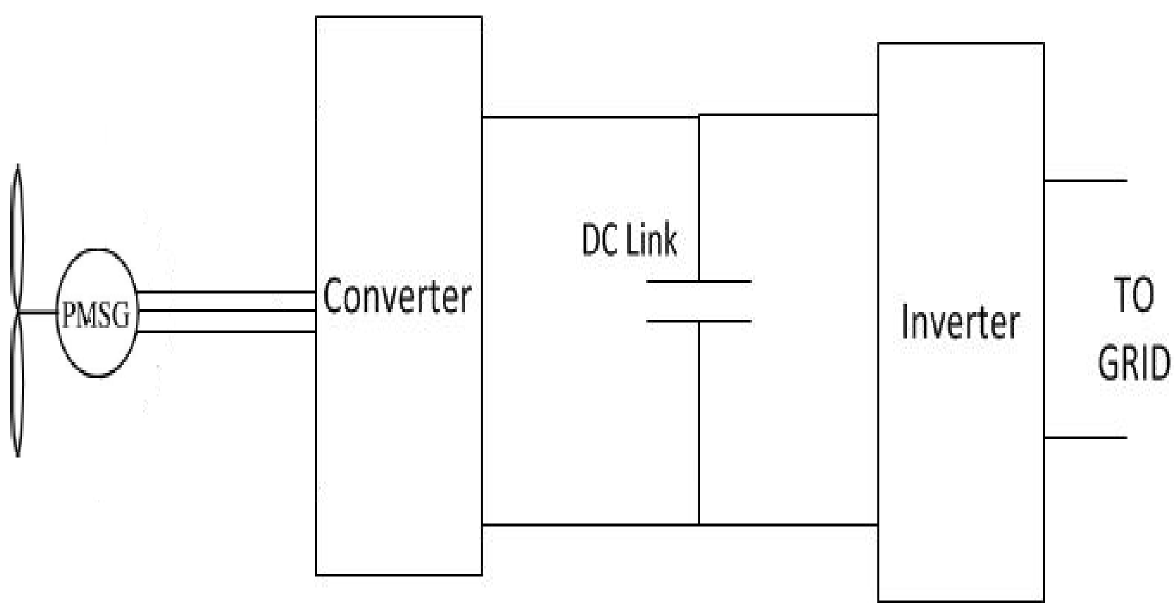

Figure 5 Block diagram of PMSG based WECS

Vector control technique is employed in both the sides to control the inverter and control so as to meet the required power requirements. In the generator side, MPPT technique is employed to absorb maximum power and the output from the MPPT is given as signal to the controlling part of the rectifier. Thus the main objective of the generator side converter is to make sure that maximum power is always absorbed from the wind turbine. There is also an additional job which needs to be done to minimize the losses in the generator circuit by regulating the d axis current in the circuit to the minimum possibel value. The d axis current can also be used for other purposes like for employing flux weakening which is done in this part to operate the machine in above rated speed or to strengthen the field flux. Both these can be achieved by adjusting the d axis circuit current such that it will produce a demagnetizing effect or magnetizing effect on the machine. As mentioned earlier, care should be taken while employing this. There is a chance of magnets going to saturation mode while flux strengthening or to become demagnetized while doing demagnetization.

In the Grid side, the main objective is to provide the the required power even at any operating conditions. Here, the word power is used which implies not just the active power but it means both active and reactive power and the circuit must be capable to provide both the active and reactive power at the reqired levels. This is made possible by using vector control technique in the grid side inverter. An additional job is also ther for the converter controlling circuit here. During operating conditions, if there is no controlling applied for the DC link capacitor voltage, then the voltage may deteriorate to some new value. Tjis can happen because of the disturbances in the circuit and also because of another reason. In the PWM circuit, all components are taking power from the DC link and so it has to supply for the small resistive losses in the control circuit. Thus a control must be designed to make the DC link voltage constant. The control strategy can be designed either in the generator side or the grid side and as the generator side is already having two specific control activities to be done, it is designed such that the grid side inverter must make sure that the the dc link voltage is remaining at a constant value without any fluctuation even when a disturbance occur at either grid or the generator.

5.2 MPPT Control Technique

For controlling a variable wind speed generator below the rated wind speed, the control is achieved by controlling the generator electromagnetic torque thereby controlling the generator speed. Above the rated wind speed, the controlling is done by pitch controlling which is done by changing the angle of contact of the blade thereby changing the rotational speed of the wind turbine. Above the rated wind speed, controlling is done for the safety of the wind turbine which otherwise may result in damage to the whole system. But below the rated wind speed, controlling is done mainly to increase the power intake of the system. In olden times, when fixed speed wind turbines were used, it was not able to absorb maximum power from the system as the system can always operate at a fixed speed and so can only absorb a fixed rated power even when the wind power availability was high. This was a huge disadvantage in those systems and this eventually resulted in the decline of the fixed speed WECS. By the introduction of power electronic converters, it was able to operate the turbine at any speed required and thus it is able to absorb variable power from the wind according to the wind availability.

MPPT scheme otherwise called as Maximum Power Point Tracking method is a control technique which can be implemented in any power generation systems so as to increase the power intake from the system. This one and only objective of this scheme is to absorb the maximum possible power from the system whatever the condition may be. This can be achieved by adjusting the turbine speed in such a way that the optimal tip speed ratio is maintained. For any specific wind turbine there exists a specific tip speed ratio which when applied will make the wind turbine operate at the maximum coefficient of power point. When machine is operated at this point, it will be possible to absorb the maximum power from the system. Tip speed ratio is actually the ratio between the wind velocity and the rotational speed of the generator. So in order to make it a constant even when the wind velocity is changing, the only way is to change the generator rotational speed to a corresponding value such that the ratio of wind velocity to the rotational speed remains a constant. Thus in all the MPPT techniques, the main objective is same which is to adjust the rotational speed to a corresponding value to make the tip speed ratio constant. For each MPPT technique, the method used for achieving this is different. Figure (**Figure *1***) shows the typical characteristics of a wind turbine which is operating at different wind speeds, where P_M and ω_M are the mechanical power and mechanical speed of the turbine, respectively. The P_M versus ω_M curves are obtained with the blade angle of attack set to its optimal value. Here, the mechanical power, turbine speed, and the wind velocity are all expressed in per-unit terms which is done for the convenience in discussion. To get the per unit value, every values are divided by the rated corresponding values. The rated wind velocity considered here is 15m/sec. Thus the wind velocities are divided by 15 to get the per unit value. For a given wind speed, each power curve has a maximum power point (MPP) at which the optimal tip speed ratio is achieved. To obtain the maximum available power from the wind at different wind speeds, the turbine speed must be adjusted so as to ensure its operation at all the MPPs. The trajectory of MPPs represents a power curve, which can be described by

$$P_M = K\,\omega_{opt}^3 \qquad (11)$$

The mechanical power captured by the turbine can also be expressed in terms of the torque:

$$T_M = P_{M*}\,\omega \qquad (12)$$

where *TM* is the turbine mechanical torque. Substituting (12) into (11) yields

$$T_M = K\,\omega_{opt}^2 \qquad (13)$$

Thus it is seen from the equation that the optimum rotational speed, which needs to be maintained so as to absorb maximum power, is directly proportional to the electromagnetic torque. Thus by adjusting the torque of the machine, it is possible to operate the machine at the optimum speed required. The equations above which shows the relation between the generated mechanical power, turbine rotational speed, and electromagnetic torque of a wind turbine can be used to determine the optimal speed or torque reference to control the generator and thereby to achieve the MPP operation. There are different control schemes which have been developed to perform the maximum power point tracking so as to absorb the maximum possible power.

As it is already mentioned, the MPPT technique can be implemented by different proposed methods. Every method has the same objective which is to maintain the tip speed ratio at an optimum value by adjusting the rotational speed. By the difference is in the method of acquiring this objective. The different types of MPPT schemes are detailed are as follows: a) MPPT with Optimal Torque Control, b) MPPT with Optimal Tip Speed Ratio c) MPPT with Turbine Power Profile. They are detailed in the next section.

5.2.1 MPPT with Turbine Power Profile

This method of maximum power point tracking is based on the power versus wind speed curve obtained from the manufacturer for a specific wind turbine. By plotting the power against rotational speed for different wind velocity, it is able to get a plot of the maximum power values for each different wind velocities. This plot is called a power curve and it defines the maximum power that can be produced by a turbine at different wind speeds. For this, the wind speed needs to be measured at each and every second and this is done by a wind speed sensor. Thus, for this type of MPPT scheme, it requires a wind speed sensor which is small drawback for this scheme. According to the MPPT profile provided by the manufacturer, the power reference P_{ref} is generated and sent to the control system of the generator. The control system compares the obtained power reference with the measured power *Pm* from the generator to produce the control signals for the power converters. By the control operations, the generated power is then made equal to the reference value obtained and this is done by controlling the current in the circuit thereby controlling the electromagnetic torque. It is noted that the power losses of the gearbox and drive train in the above analysis are neglected and, therefore, the mechanical power of the generator *Pm* is equal to the mechanical power *PM* produced by the turbine. This assumption seems legit in PMSG based WECS as the gearbox is usually absent.

5.2.2 MPPT with Optimal Tip Speed Ratio

In this method, to obtain the maximum power from the system, the tip speed ratio is being used. It is already mentioned that for any wind turbine system, there exists an optimum tip speed ratio for which maximum power can be obtained. This optimum tip speed ratio is usually provided by the manufacturer or can easily be found out by experimental methods. If this optimum speed is obtained, then the required optimum reference rotational speed can be found out if the wind velocity is known. So, for this method also, a speed sensor is required to measure the wind velocity. Thus by dividing it with the optimum tip speed ratio, the optimum rotational speed is obtained and this signal is send to the control system. This rotational reference speed can be converted into reference torque signal. The electromagnetic torque is directly proportional to the q axis current and thus the reference q axis current is obtained. This is then compared with the actual q axis current and the error is given to a PI controller and then given as signals to the PWM controller. Thus the controller will make the q axis current equal to the reference optimum q axis value at steady state, which makes the electromagnetic torque generated in the system adjusted such that the rotational speed will be equal to the optimum reference value and thus the system absorbing the maximum power. Thus the maximum power point tracking is obtained. But in this scheme also, there requires a need for a wind speed sensor.

5.2.3 MPPT with Optimal Torque Control

The maximum power operation can also be achieved with optimal torque control according to Equation (13). Observing the equation, it is seen that the turbine mechanical torque T_m is a quadratic function of the turbine rotational speed. If the gear ratio and the mechanical power losses if is neglected, then the turbine mechanical torque T_{mech} and speed ω_m can be easily converted to the generator mechanical torque *Tm* and speed ω respectively. In this MPPT scheme with optimal torque control the mechanism is as follows. The generator speed ω_m is calculated and is used to compute the desired torque reference T_{ref}. The coefficient for the optimal torque T_{opt} can be calculated according to the rated parameters of the generator. Through the feedback control, the generator torque T_m will be equal to its reference T* in steady state, and the MPPT is realized. It is noted that there is no need to use the wind speed sensors in this scheme.

Any of the three above mentioned methods can be used for MPPT control as all three are equally efficient and here, the second type control which involves the controlling using tip speed ratio is used.

5.3 Back to back Converter Control

In this WECS, a back to back converter is used which involves a controlled rectifier and a controlled inverter and a DC link which is used to connect both the parts. Both the rectifier and inverter are controlled using vector control. Vector control is mainly used for speed control of induction motors where the three phase abc current vectors are converted into two vectors which are placed at a 90 degree with respect to each other. Here, one vector will be proportional to the torque component of the machine and the other component proportional to the field component. Thus an induction machine can be controlled easily like a DC machine. This vector control is not limited for induction machines and can be implemented in any machine for the ease of control. In this system, vector controlling is implemented in both the rectifier and the inverter independently with each side having an independent job. Thus the whole system can be divided into two sides namely the machine side or the generator side and the grid side. For the ease of designing, both the sides are designed separately and finally they are put together to from the whole wind energy conversion system. In the generator side, the main aim of control system is to absorb maximum power possible from the system and also to minimize the copper loss by minimizing the current. The second aim is made possible by controlling the d axis current which doesn't have any role in torque production and thus minimizing it would not result in any serious consequence. In the grid side control system, the main objectives are to maintain a constant dc link voltage, which is done by controlling d axis current, and to provide the power to the grid at the required power factor, which is done by controlling the q axis current as reactive power is directly proportional to the q axis current. Thus the main objectives of the generator side control are as follows:

a) Implementing MPPT technique to absorb maximum power
b) Minimizing the copper loss by reducing the d axis current

Similarly, the objectives of the grid side control system are as follows:

a) Supply the generated power at required power factor to the grid
b) Maintain the Dc link voltage at a constant value even during disturbances

5.4 Machine Side Converter Control

Many different types of controlling schemes can be used in a synchronous generator based on the requirements or the objectives. The *d-axis* stator current of the generator can be set to zero during the operation so as to minimize the copper loss or can be set so as to strengthen or weaken the magnetic field. The objective of the control defines the alignment of d and q axis components in the system. So for each purpose different type of control schemes are used. For instance, the *d-axis* stator current of the generator can be set to zero during the operation to achieve a linear relationship between the stator current and the electromagnetic torque. Alternatively, the generator can be controlled to produce maximum torque with a minimum stator current. Similarly, another approach is to operate the system with unity power factor. Here, the Zero d- axis current control (ZDC) is used. These different schemes are explained in the next section.

5.4.1 Zero d-Axis Current (ZDC) Control

The zero d-axis current control can be realized by resolving the three-phase stator current in the stationary reference frame into d- and q-axis components in the synchronous reference frame. Then the d axis component of the current is controlled to be zero. Substituting the value of d axis in the equation, the stator current equation will result in the following form:

$$\widehat{i_s} = i_{ds} + j i_{qs} = j i_{qs} \quad (14)$$

$$i_s = \sqrt{(i_{ds}^2 + i_{qs}^2)} = i_{qs} \quad (15)$$

where $\widehat{i_s}$, the stator current space vector and i_s represents its magnitude, which is also the peak value of the three-phase stator current in the stationary reference frame. Applying the values obtained in the equation for electromagnetic torque, the electromagnetic torque of the generator

$$T_e = 3/2(\lambda_r i_{qs} - (L_d - L_q) i_{ds} i_{qs}) \quad (16)$$

But as here, $L_d = L_q$ as cylindrical rotor is considered and thus it can be simplified into,

$$T_e = 3/2(\lambda_r i_{qs}) \quad (17)$$

Here P is the pole pairs and λ_r is the rotor flux linkage produced by permanent magnets in the PMSG. The above equation indicates that when $i_d = 0$, then the generator torque is proportional to the stator current i_s, the torque and stator currents are having a linear relationship if the rotor flux linkage λ_r is a constant which is the case in a PMSG machine. This condition is similar to torque production in a DC machine with a constant field flux. In Dc machine the electromagnetic torque is proportional to the armature current. Thus it is able to make a synchronous generator equivalent to a DC machine. It is assumed that the stator resistance R_s is negligible. Also the rotor flux linkage is considered to be aligned with the q-axis of the synchronous reference frame. All vectors together with the *dq-axis* frame rotate in space at the synchronous speed, which is also the rotor speed of the generator ω_r. The stator current vector i_s is perpendicular to the rotor flux vector λ_r. The stator voltage magnitude is thus given by the equation:

$$V_s = \sqrt{(V_{ds}^2 + V_{qs}^2)} = \sqrt{((\omega_r L_q i_q)^2 + (\omega_r \lambda_r)^2)} \qquad (18)$$

5.4.2 Maximum Torque per Ampere (MTPA) Control

This scheme of vector control is used to generate the required torque at the minimum possible current value. The equation for torque is already mentioned above in equation (16) and by analyzing this equation, it is seen that the torque is a function of d and q axis stator current iqs and ids for a given rotor flux linkage. Thus it implies that same torque can be produced by a generator for different values of d and q axis currents where d and q axis currents are the flux producing and the torque producing components of current in the stator respectively. So it is possible to produce same torque with minimum stator current by adjusting the ratio of *ids* to *iqs.* For a given stator current *is,* the magnitude of its d-axis current can be calculated by

$$i_{ds} = \sqrt{i_s^{\,2} - i_{qs}^{\,2}} \qquad (19)$$

Substituting the above equation into (16), the generator torque can be expressed as a function of *i,,.:*

$$T_e = 3/2(\lambda_r iqs - (L_d - L_q)(\sqrt{is^2 - iq^2})iqs) \qquad (20)$$

In cylindrical type generator, as both the *d-axis* and q-axis inductances are equal, the equation above can be simplified to

$$T_e = 3/2(\lambda_r iqs) \qquad (21)$$

Thus only q axis current is contributing for the torque production. So, to implement maximum torque per ampere control scheme, the best possible way is to reduce the d axis current to zero and thus the stator current essentially becoming equal to q axis current. The same condition is seen in the zero d axis current control and thus for a non-salient pole generator, both the zero d axis current control and maximum torque per ampere control are the same. For salient pole machine, the case is different as L_{ds} is not equal to L_{qs}. So the equation becomes complex. But here only a cylindrical machine is considered and thus both ZDC and MTPA scheme are the same. Thus the MTPA scheme is used so as to produce a desired torque with a minimum stator current. This maximizes the utilization of the stator current and minimizes the stator winding losses which is dissipated in the machine.

5.4.3 Unity Power Factor (UPF) Control

In this controlling method, the aim is to operate the machine at unit power factor. If the voltage drop in resistance is neglected, then the equation for q axis and d axis stator voltage will be:

$$V_{ds} = \omega_r L_q i_{qs} \qquad (22)$$

$$V_{qs} = \omega_r \lambda_r - \omega_r L_d i_{ds} \qquad (23)$$

Thus the stator phase voltage phase angle can be calculated by finding $\tan^{-1}$ of V_{qs}/V_{ds}. Similarly, $\tan^{-1}$ of iqs/ ids is calculated to find the phase angle of stator current. Then for unit power factor, the condition is:

$$\theta_{vs} - \theta_{is} = 0 \qquad (24)$$

Substituting the values from equation (22) and (23) in equation (24) and then solving the equation, the condition for the control scheme is obtained which is:

$$i_{qs} \leq \lambda_r \Big/ 2\sqrt{L_d L_q} \qquad (25)$$

Thus by satisfying this condition, unit power factor control can be implemented in a synchronous machine.

Any of these methods can be implemented in a system according to the requirements. These schemes are common schemes for both cylindrical and salient pole machine. As we are considering only cylindrical type, both the ZDC and MTPA control schemes are the same. This zero d axis current control is implemented in the system so that torque can independently have controlled by the q axis current and d axis current is maintained at zero value so that the copper loss can be minimized to the least possible value.

5.4.4 Implementation of Vector Control

By using ZDC control, we are able to control the torque by regulating the q axis current. To extract maximum power from a wind turbine, as in figure (**Figure *1***). The machine is operated at a required rotor speed for each corresponding value of wind speed. This can be attained if we are able to change the electromagnetic torque to a certain value that, when this toque is applied, then it may cause acceleration or deceleration in the machine and thereby causing the machine to change its speed until it reaches the desired optimum speed ω_{opt}. Thus to extract maximum power for a particular wind, we are calculating the optimum torque T_{opt} and this signal from the MPPT is fed to the vector control part. As torque and current are having a direct relation, the equivalent current for this optimum torque can be found. Then by using a PI controller the actual current is compared with the reference value and is given as input to the PWM signal generator. The *d*-axis current component *idr* is set to zero. Voltage feed forward compensation; ΔVsd and ΔVsq are added into the control strategy to improve the dynamic response. The output from this can be used to give the input gate signals for the converter. The block diagram for the machine side control is shown in figure(**Figure *6***).

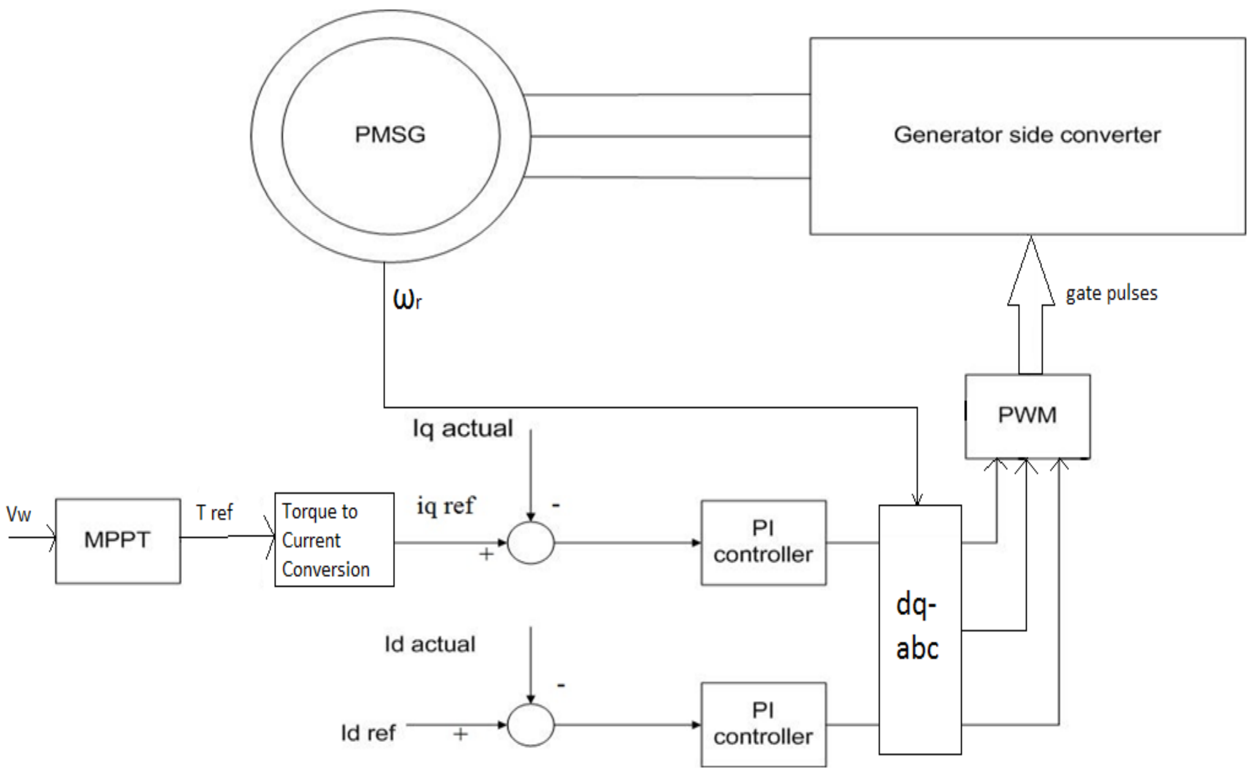

Figure 6 Generator side control

The electromagnetic torque generated in a machine is given by:

$$T_e = 3/2(\lambda_r i_{qs} - (L_d - L_q)^* i_{ds} i_{qs}) \quad (26)$$

As cylindrical machine is considered here, $L_d = L_q$. Thus the equation becomes:

$$T_e = 3/2(\lambda_r i_{qs}) \quad (27)$$

In zero d axis current control scheme, for making the torque directly proportional to q axis current, d axis current is to be maintained zero. But for a cylindrical machine, even if d axis current is non zero, the electromagnetic torque is still only dependent on the q axis current. Thus the torque can be easily controlled by the q axis current without making the d axis current zero. Thus for a cylindrical machine, controlling of torque can be achieved and at the same time d axis current can be either minimized to zero or the d axis current can be controlled so as to strengthen or weaken the flux as required.

5.5 Grid Side Converter Control

The main objectives in grid side are mainly to control the DC link voltage at a fixed value and also to supply the absorbed power from the system at the grid required power factor. The three-phase converter the grid side supplies the generated power into the grid, keeping the DC-link voltage constant and adjusting the amount of the active power and the reactive power delivered to the grid during load transients or wind variation. The PI controller employed in the controller stabilizes the DC link voltage by reducing the error with the reference value thereby making it equal to the reference value. Hysteresis current controllers are used to regulate the output currents and voltage in the inner control loops and the DC voltage controller in the second loop. The vector control scheme used is designed based on a synchronously rotating reference frame. The angular velocity of the rotating axis system ω is set in the controller and defines the electrical frequency at the load. The voltage balance across the inductor *Lf* is given by

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = R_f \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + L_f \frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \tag{28}$$

where *Lf* and *Rf* are the filter inductance and resistance respectively; *ea* , *eb* and *ec* represent voltages at the inverter output; *va* , *vb* and *vc* represent the grid voltage components voltages; ia , ib and ic are the line currents. Transformation in the rotating reference frame is calculated as follows

$$V_d = e_d - R_f i_d - L_f(di_d/d_t) + \omega L_f i_q \tag{29}$$

$$V_q = e_q - R_f i_q - L_f(di_q/d_t) - \omega L_f i_d \tag{30}$$

$$C(dU_{dc}/dt) = 3/2((V_d/U_{dc})i_d + (V_q/U_{dc})i_q) - i_{dc} \tag{31}$$

where ed and eq are the inverter d-axis q-axis voltage components respectively, vd and vq are the grid voltage components in the d-axis q-axis voltage components respectively, Udc is the dc-bus voltage, idc is the DC-bus current. The instantaneous power in a three phase system is given by

$$P(t)= V_a i_a + V_b i_b + V_c i_c = [V_a\ V_b\ V_c][\ i_a\ i_b\ i_c]^t \qquad (32)$$

Using d-q transformation, the active and reactive power is given by:

$$P= 3/2(V_d i_d + V_q i_q) \qquad (32)$$

$$Q= 3/2(V_d i_q - V_q i_d) \qquad (33)$$

If the grid voltage space vector u is oriented on d-axis, then:

$$V_d= V \qquad (34)$$

$$V_q= 0 \qquad (35)$$

Therefore, equations (20-21) may be expressed below:

$$e_d= R_f i_d + L_f(di_d/d_t) - \omega L_f i_q + V \qquad (36)$$

$$e_q= R_f i_q + L_f(di_q/d_t) +L_f i_d \qquad (37)$$

Then the active power and reactive power can be expressed as:

$$P= 3/2(Vi_d) \qquad (38)$$

$$Q= 3/2(Vi_q) \qquad (39)$$

A schematic block diagram showing the control strategy in the grid side is shown in the figure(**Figure *7***)

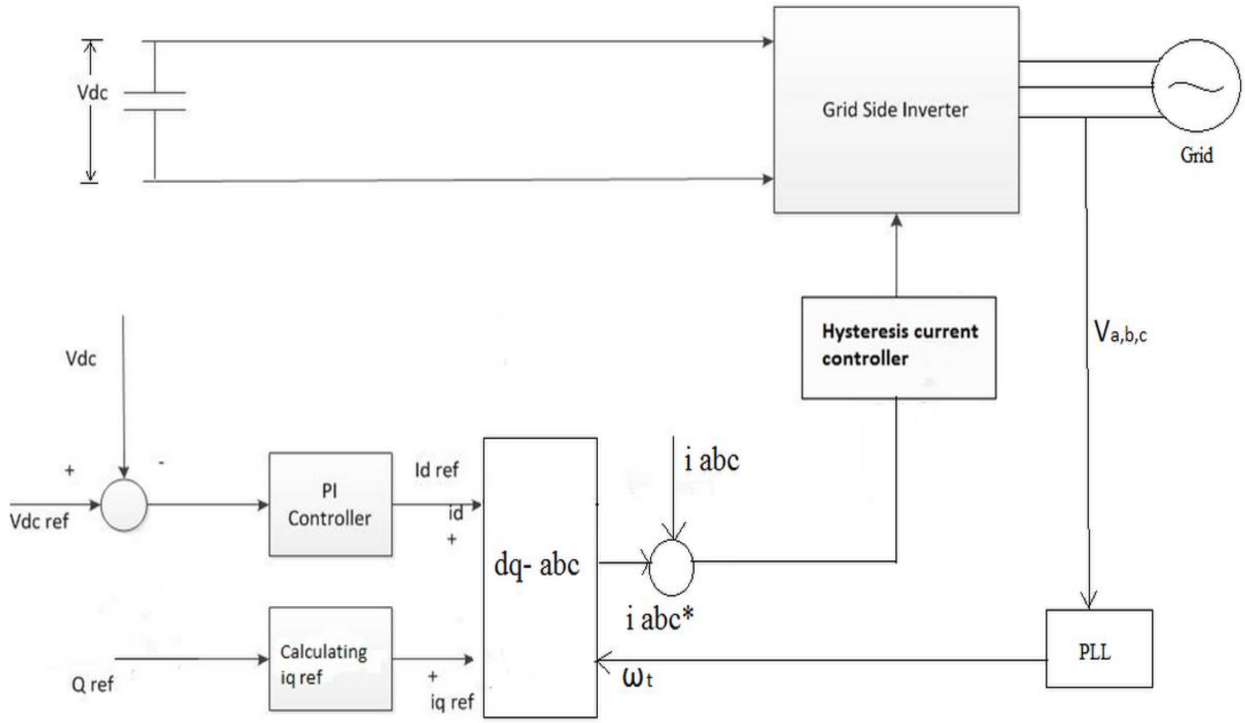

Figure 7 Grid side control

Thus active and reactive power can be controlled independently by this control scheme by regulating the d axis current and q axis current respectively. Two closed-loop controls which are for the active and reactive power separately are designed here. The error signal obtained from comparing the actual dc link voltage (Udc) and the reference dc link voltage ($U_{dc\ ref}$) is fed to a PI controller and thus getting the required control signal which forms the required reference current for the d-axis current.

As per equation (39), it is observed that a direct relation exists between the q axis current and the reactive power and is independent of any other parameters except V which is equal to q axis voltage as the voltage vector is aligned along the q axis of the vector. Thus to control the reactive power independently, it can be done by controlling the q axis current which is easily possible. Thus the equivalent reference q axis current is calculated from the reference value of reactive power which is the grid required value. Also, the actual q axis value of current value is also found using current measurements devices. These signals are then given to a hysteresis current controller after converting it to abc form from d-q form. Hysteresis controller is also receiving inputs from the q axis current and the reference d axis current which I also converted top abc sequence and then given as input to the controller. The q axis reference value is obtained from the PI controller

Here, an additional method called decoupling is used during controlling. In the equations, by analyzing, it is understood that in the equation of q axis current, d axis current terms are present and in the equation of d axis current, q axis current terms are present. This situation makes it hard to control because, while trying to control d axis current, the values for q axis current is changed and vice versa. Thus it is required to convert the q axis current’s equation free of d axis current terms and d axis current’s equation free of q axis current terms. This is made possible by the method of decoupling. This makes it easy to control both the values and finally making every values equal to the reference value so as to get the required results. PWM is used to produce the control signal to control the grid-side converter.

Chapter 6

Simulation and Results

6.1 Introduction

The system is built using Matlab/Simulink. This section presents the simulated responses of the WECS under variable wind speeds. The simulation is done as two parts. First part shows the generator side simulation which includes the generator and converter arrangement. It is then connected to a dc voltage, which represent the grid side part through a resistor (**Figure *8***). Using the resistor and the dc voltage source, it is able to represent the whole grid side where resistor represents the losses in the system. When the generated voltage is more than the dc voltage, it implies the power is transferred from the generator sides to the grid side. In this part, the controlling of the converter is done using a pair of PI controllers and PWM technique. MPPT technique is also implemented here so as to absorb maximum possible power from the system.

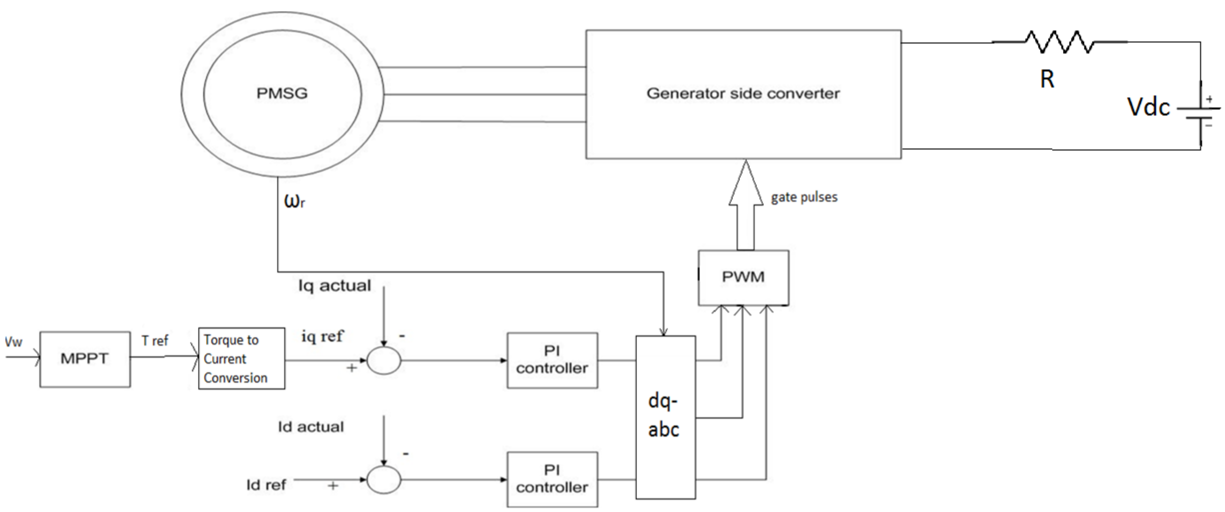

Figure 8 Equivalent representation of WECS using a DC voltage source

The second part includes the simulation of grid side part which includes an inverter which is connected to grid through a filter. Here, the generator is represented by a dc voltage source connected in series with a resistor which represents the losses in the machine. The DC voltage value is kept at a higher value than the reference value so that power is from generator side to grid side. Finally, to create the whole wind energy conversion system, the grid side part can be connected to the generator side part. Thus it will be able to generate maximum power from the available wind with reduced copper loss that also at required reactive power requirement.

6.2 Machine Side Simulation

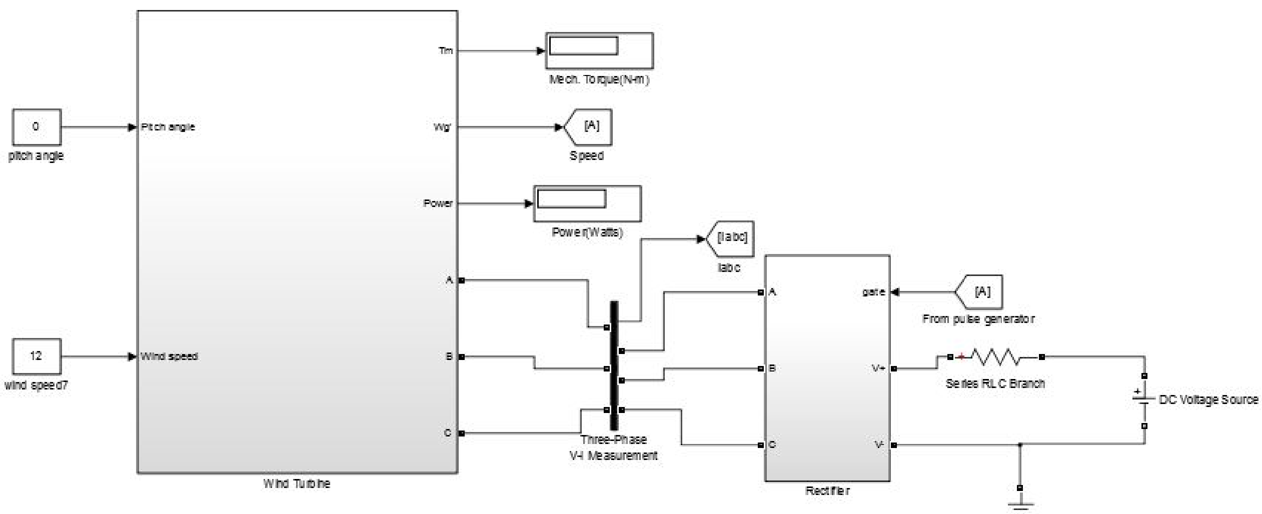

Figure 9 Generator side simulation

In the figure shown figure (**Figure *9***), the machine side is shown. Here, the inputs are given at one side which is the pitch angle and the wind speed. Then at the output side PMSG will be generating power and this electrical power is taken the electrical connection from the machine and is connected to the rectifier. This rectifier is then connected to a series connection of resistor and a DC voltage. The power, mechanical torque and speed are measured. Inside the wind turbine, the mechanical part is connected to the electrical part as shown in **Figure *9***. Here the mechanical torque is generated from the wind speed, pitch angle and rotor speed as mechanical torque is dependent on wind speed as explained by the graph in **Figure *1***. This simulation is already explained in Chapter 2 and the simulation is shown in **Figure *2***. Thus the mechanical torque is obtained and this mechanical torque is given as input to the mass drive train from which the speed can be calculated from mechanical and electromagnetic torque as shown in the **Figure *3***. However, in this model no gear drives are used to increase the speed and so a direct driven machine is used. Inertia factor and rotational damping coefficient will be affecting the speed here. Thus from the output of the generator, the rectifier is connected which is a fully controlled three phase

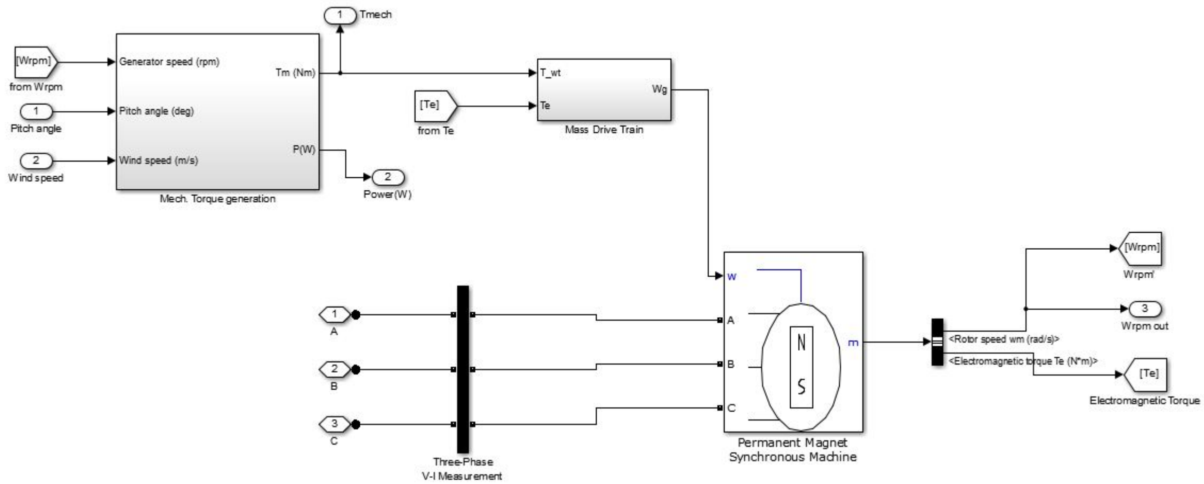

Figure 10 Wind turbine simulation

rectifier. The rectifier switching is controlled by the control signals coming from the PWM generator which compares the reference signal with a triangular wave signal and thus producing the On and Off signals. The control circuitry consists of MPPT block which is then

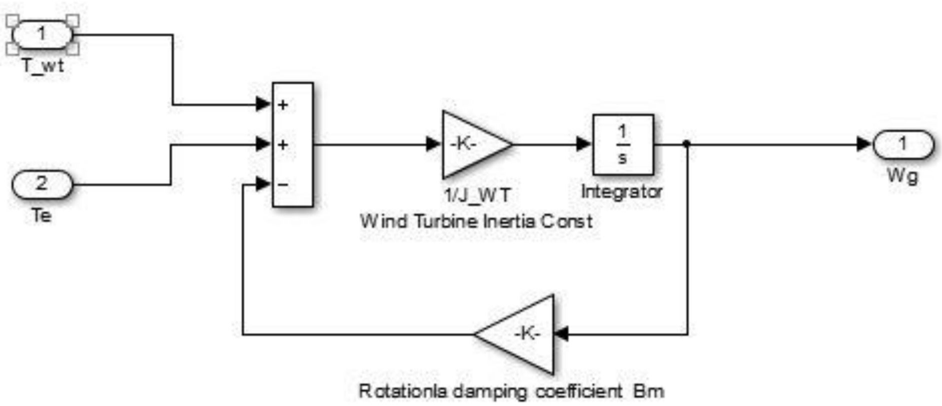

Figure 11 Mass drive train model

connected to produce current signals and from the current signals, the required pulses are generated. The vector control part is shown in the **Figure *12***. Here from rotor wind speed, the optimum value of Torque is calculated in the MPPT block. This torque is then converted to current using the equations mentioned in Chapter 3. Thus we are getting the required q axis current

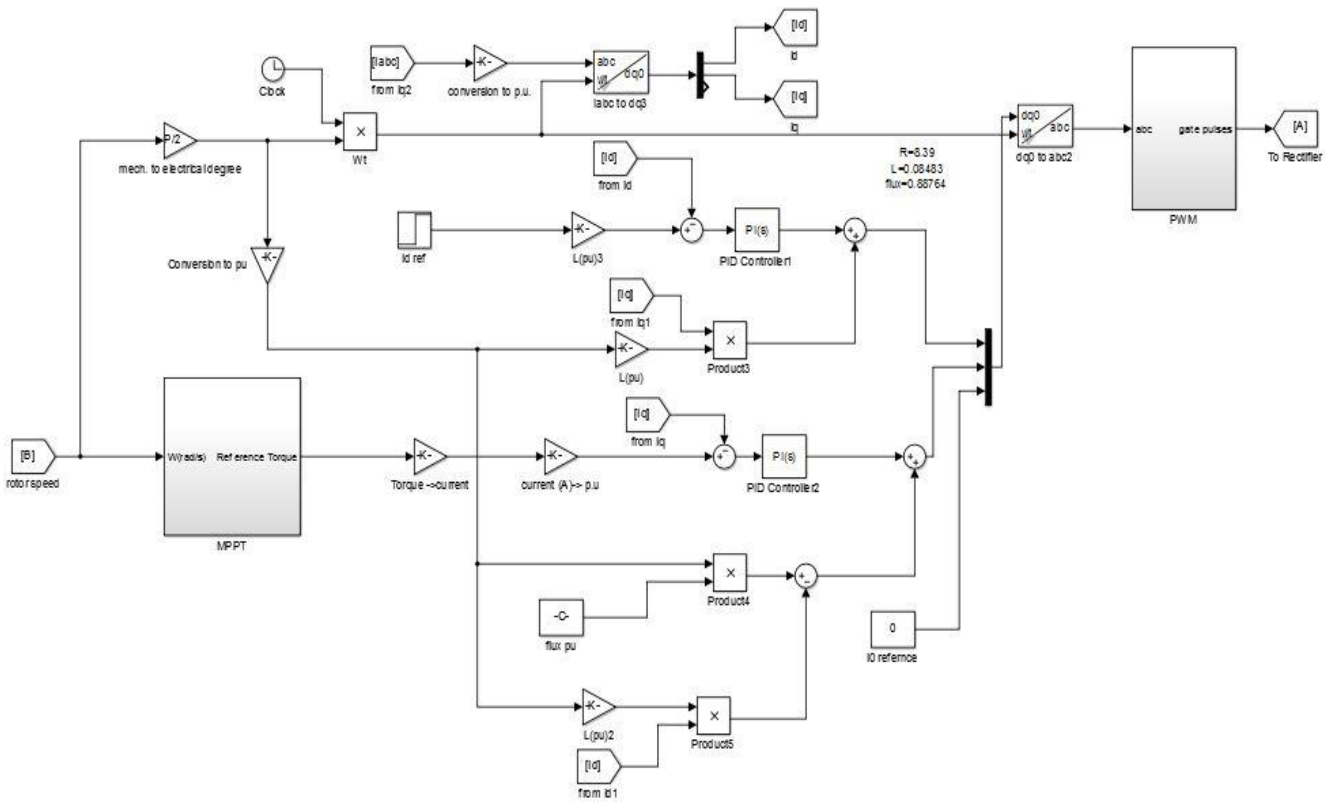

Figure 12 Generator side vector control simulation

reference. Similarly, a d axis current reference is also set and both these are given as inputs to the PI controller after comparing with the actual current values. Thus PI controller will work in such a way that the error signal is minimized. The output is then given to the PWM block which produces required gate signals after comparing the obtained reference signal with the triangular waveform. The obtained waveform results are shown below. Wind velocity is varied from base speed 12 m/sec to 7 and then again to 11m/sec. Corresponding change in rotor speed is shown in **Figure *13***. Initially motor was run without employing MPPT and after it reached certain value controlling is activated. Then the rotor speed is changed and adjusted so that maximum power is extracted at every wind speed. The corresponding waveforms for mechanical and electrical torque and for power generated are shown in **Figure *14***. The reference torque, which is the optimum value, is also shown along with the actual mechanical torque. It can be observed that when the speed is

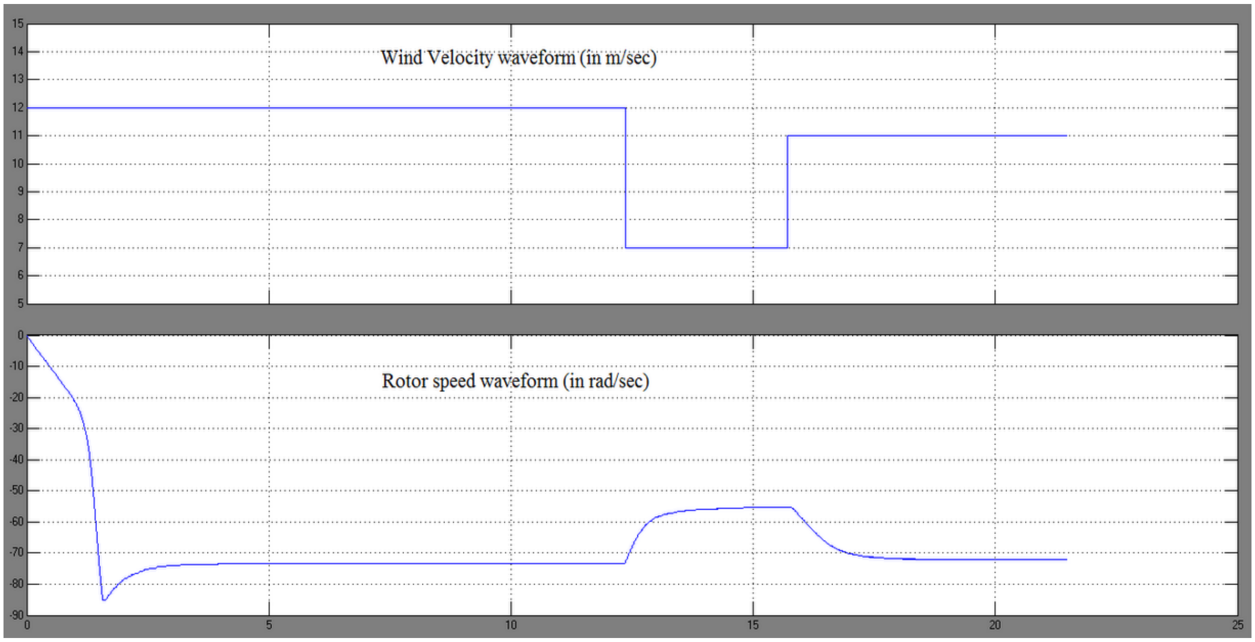

Figure 13 Wind speed and rotor speed waveform

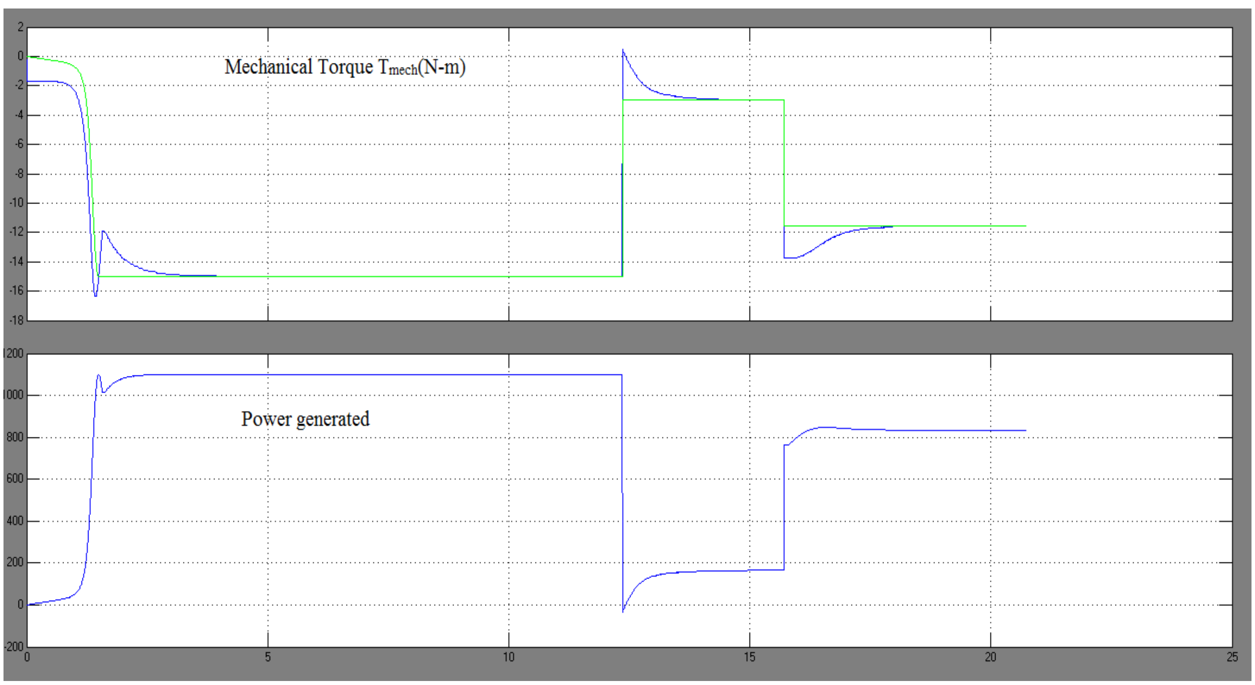

Figure 14 Torque and power waveform

changing from some value to its optimum value, the power extracted is increasing. Also d axis and q axis current waveforms are also shown. q axis current is tracing the reference value so as to extract maximum power and d axis current is going along with the reference value and thus by setting the reference to zero, we can reduce the rotor electrical losses and thus getting more efficiency. The DC output voltage produced is also shown in the figure.

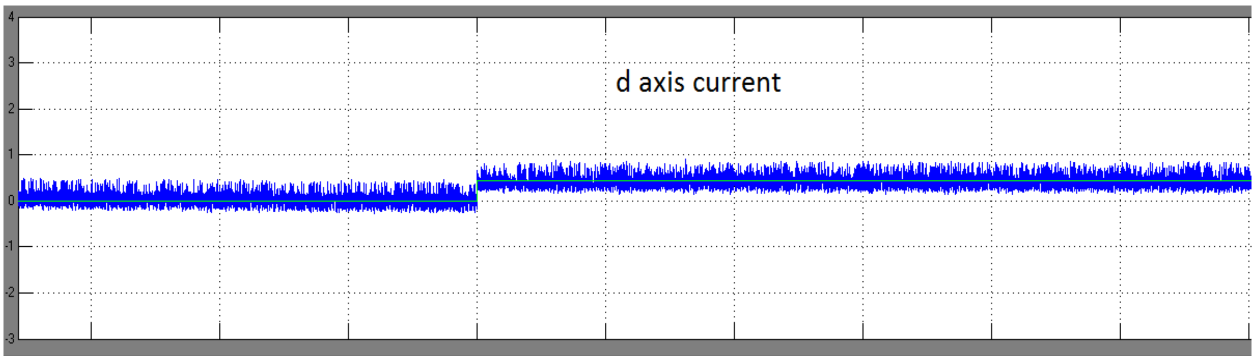

Figure 15 d axis current

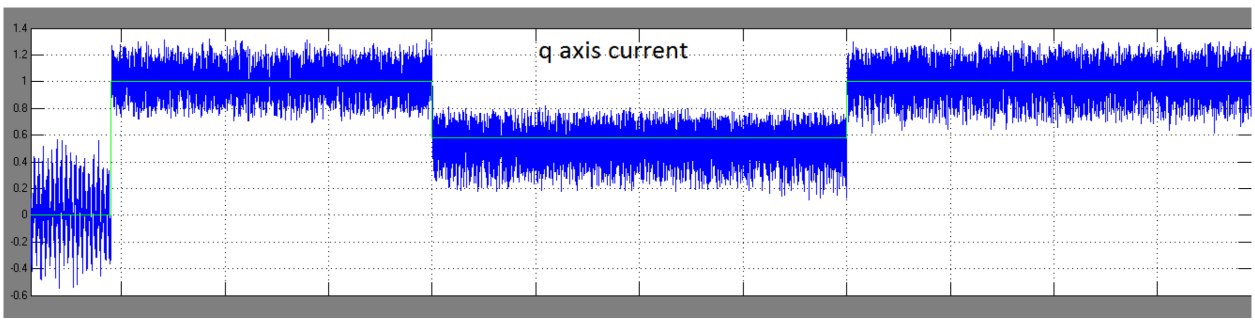

Figure 16 q axis current

6.2 Grid Side Simulation

The grid side simulation main circuit is shown in the figure (**Figure *17***). Here, the generator side complete circuit is represented by a DC voltage in series with a resistance which stands for the rotor losses. This is then connected to the inverter through a capacitor whose voltage is to be

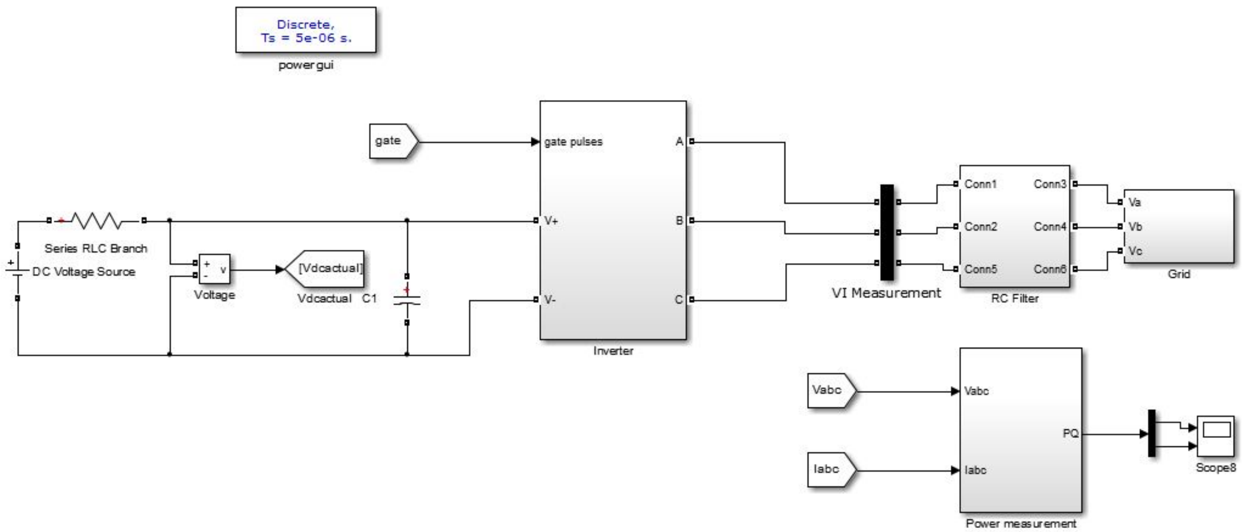

Figure 17 Grid side simulation

controlled. From this inverter, it is connected to the grid through an RC filter so as to filter out any high frequency components in the voltage. The control section of the grid side inverter is shown in the figure (**Figure *18***). A fixed capacitor dc voltage is selected and is compared with the actual

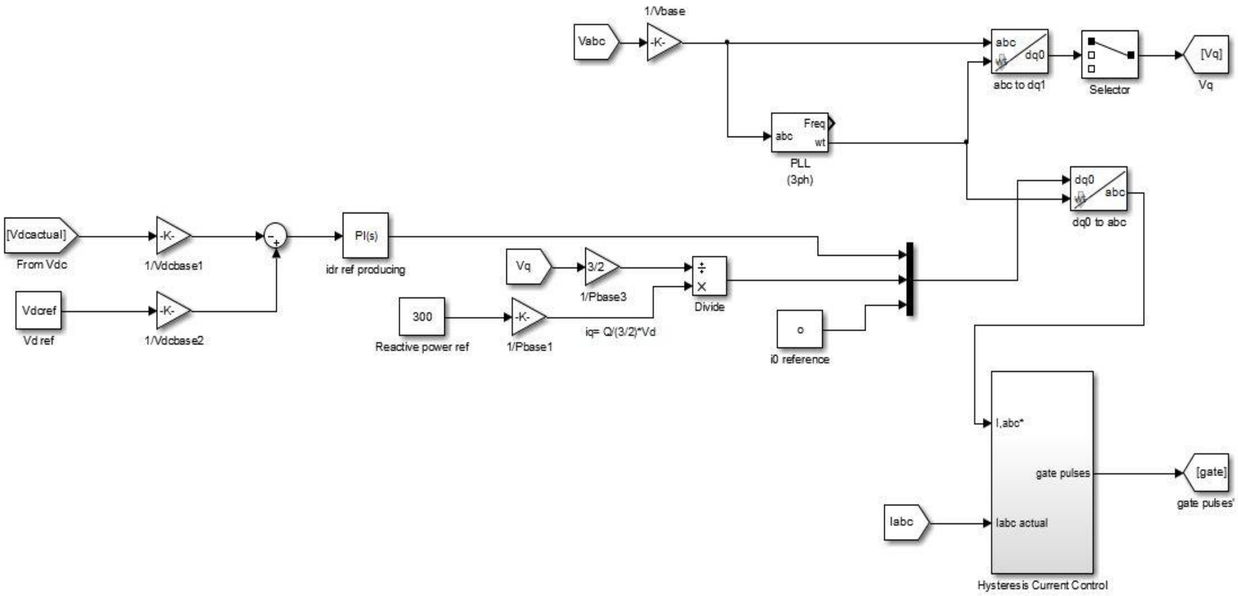

Figure 18 Grid side vector control simulation

value and the error is given to a PI controller. The output obtained is equivalent to the d axis reference value of current. Similarly, to control the reactive power flow, the required reference q axis current is calculated from the reference reactive power. Thus both these current reference values are given as input to the hysteresis current controller and that gives gate pulses which are used to control the switching sequence of the inverter. Thus by using this control, it is able to control the dc voltage across the capacitor at a fixed value even if the generator voltage is fluctuating. And similarly it is able to supply the active power completely along with the required reactive power. Thus both active and reactive power requirement can be met. The results are shown in the figure below.

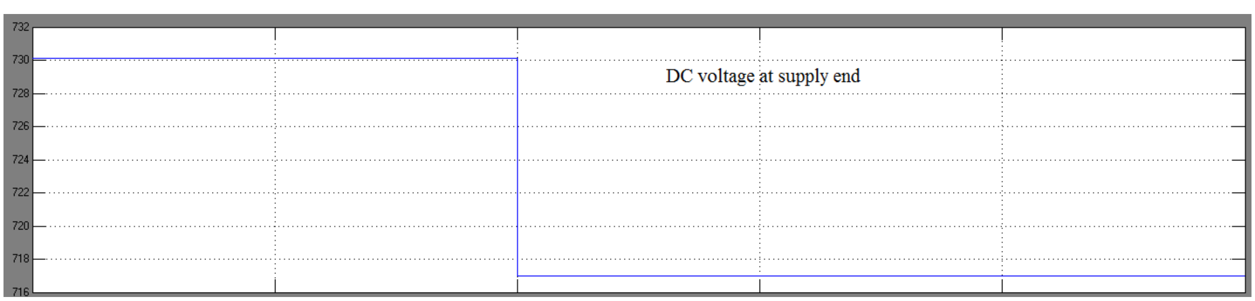

Figure 19 Dc supply voltage

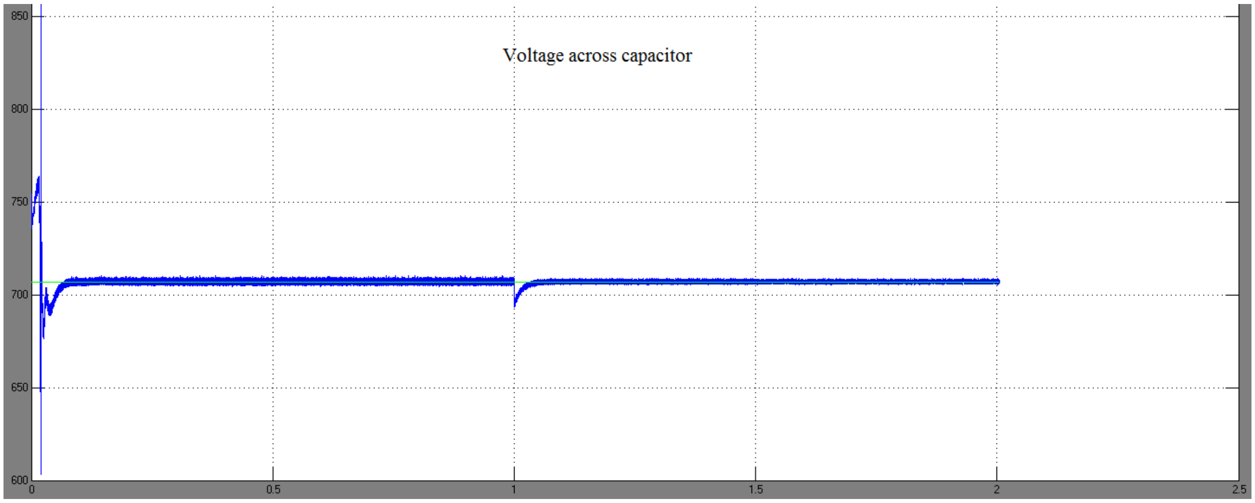

Figure 20 Capacitor voltage

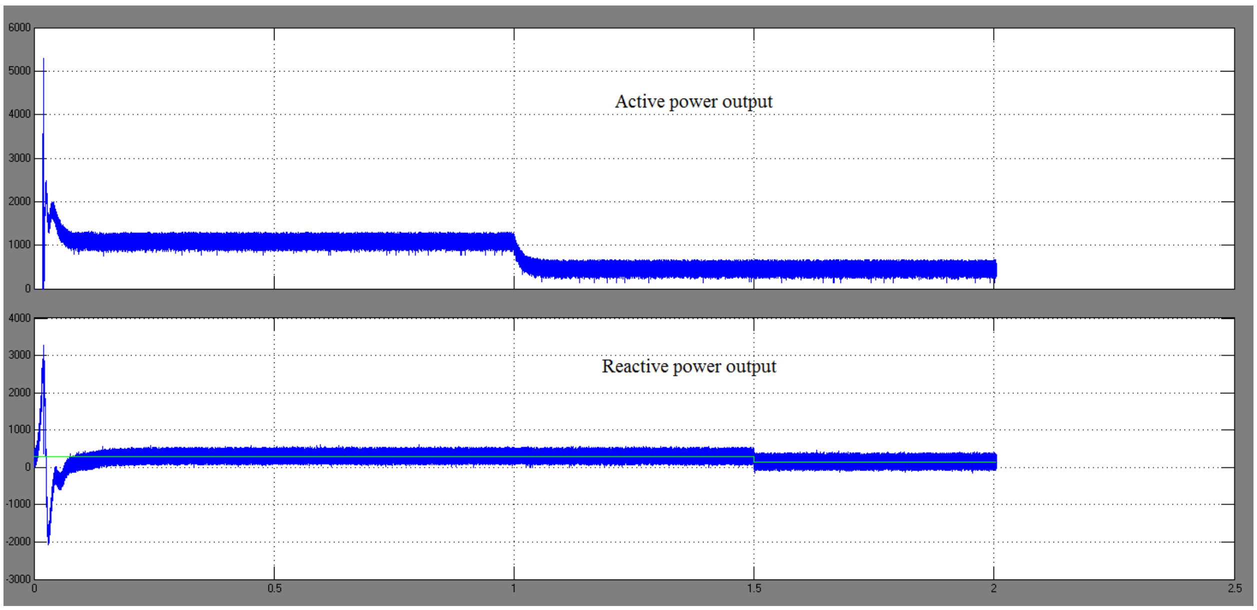

Figure 21 Active and reactive power output

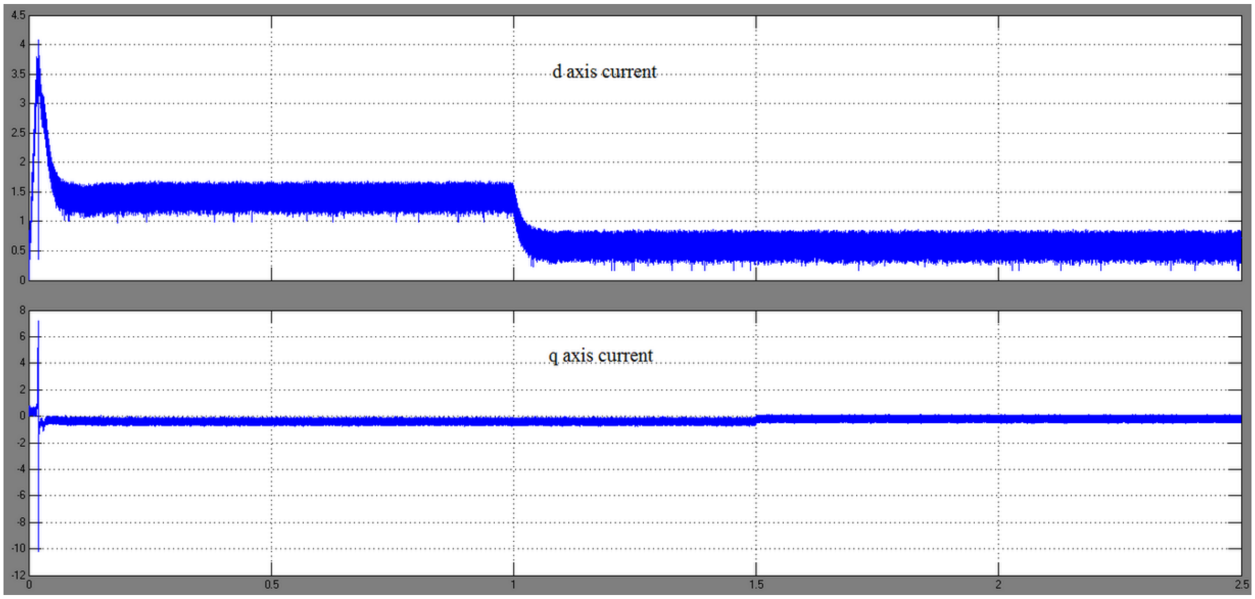

Figure 22 d and q axis current

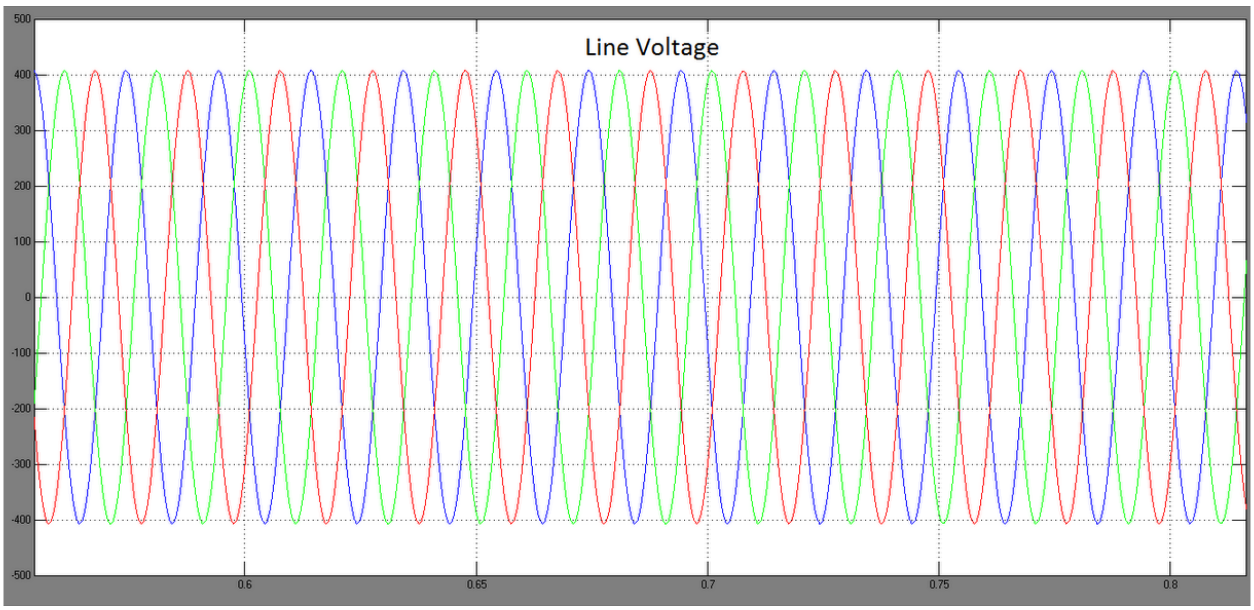

Figure 23 Line voltage

Thus by interfacing both these systems, a complete PMSG based wind energy conversion system is available which can extract maximum power for each wind velocity with the minimum possible rotor copper loss and also providing active power at required power factor.

Chapter 7

Conclusion and Future Scope

A PMSG based wind energy conversion system is studied. PMSG and wind turbine models are made. MPPT technique is used to extract maximum power from the system and is implemented using vector control method in the generator side. Zero direct axis current control is also used in the generator side so as to limit the d axis current to the least possible value so that total current and thereby the copper loss will remain at the least possible values. In the grid side converter Control techniques are implemented so as to regulate the DC link voltage at a constant value and also it is able to provide the active power at the required power factor demands. Thus an efficient way to provide electrical power from wind energy is studied.

Still there are certain major issues which can affect the performance of this system like fault occurrences etc. and some improvements have to be made so as to operate the system efficiently even during these situations. Also when comparing with DFIG based WECS, the THD introduced by the converters is also a serious disadvantage in PMSG based WECS as DFIG based WECS requires only a low rated converter and thus lesser trouble with THD. These performance improvements which can be done to the system to improve the performance are to be studied.

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