CONTROL OF WIND TURBINE DRIVEN PERMANENT MAGNET SYNCHRONOUS GENERATOR

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CONTROL OF WIND TURBINE DRIVEN PERMANENT MAGNET SYNCHRONOUS GENERATOR

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE AWARD OF THE DEGREE OF

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By

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CERTIFICATE

This is to certify that the project entitled "**CONTROL OF WIND TURBINE DRIVEN PERMANENT MAGNET SYNCHRONOUS GENERATOR**" submitted by **Ms Deepanwita Pradhan (213EE5347)** in partial fulfillment of the requirements for the award of Master of Technology degree in Industrial Electronics, Department of Electrical Engineering at National Institute of Technology, Rourkela is a genuine work carried out by her under my supervision and guidance.

The matter illustrated in this thesis has not been submitted to any other Institute for the award of any Degree to the best of my knowledge.

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ABSTRACT

Nowadays renewable energy sources are playing a major role in power sector where power generation from major conventional ways is impractical. Among these wind power system is a better choice for its own advantages like it requires less land to install wind turbines, the land near it can be used for agriculture and most important it can be used for wide range of power generation. For small scale power generation PMSG is most popular due to its better efficiency.

Here the excitation for rotor (field) is provided using a permanent magnet rather than a coil which leads to many advantages but one demerit is that the field flux cannot be controlled. Absence of field coils leads to reduction in copper losses and it can be coupled directly to generator without any gear box as it can be operated with more number of poles. In this work one machine side converter is designed which is used to maximize power taken by the turbine taken from wind at different wind speed which will enhance the efficiency of turbine. This control will be done by adjusting the duty ratio of DC-DC converter which will make the turbine to rotate at its optimum speed according to the variation in wind speed.

As the system is needed to be connected to utility grid and the grid voltage and frequency is constant so accordingly we need a grid side control system which will regulate the dc voltage output of converter and will make the grid side voltage constant. For grid connected operation of renewable energy systems the accurate determination of grid phase angle is needed which can be done by using a phase locked loop technique (PLL) and harmonics can be minimized using this control system. A grid voltage oriented vector control scheme is implemented here for the reactive power compensation, harmonic reduction and grid synchronization.

LIST OF FIGURES

LIST OF ABBREVIATIONS

WG	Wind Generator
TSR	Tip Speed Ratio
MATLAB	Matrix Laboratory
PMSG	Permanent Magnet Synchronous Generator
P & O	Perturb and Observe
PWM	Pulse Width Modulation
MSC	Machine Side Converter
Fig	Figure
GSC	Grid Side Converter

LIST OF TABLES

LIST OF SYMBOLS

P	Power captured by wind turbine
ρ	Air density
β	Pitch angle (in degrees)
A	Area covered by the blade of the turbine in m^2.
V	Wind speed (in m/s)
C_p	Wind turbine power coefficient
λ	Tip speed ratio
Ω	Angular velocity of wind turbine in rad/sec
R	Radius of blades of turbine
λ_i	Constant
E	Induced emf of generator
f	Frequency of supply
Φ	Average value of flux
T	Number of turns per phase of generator
p	Number of pair of poles in the generator
Ω_e	Angular speed of generator- phase voltage
V_R	Output voltage of rectifier or input to dc-dc converter
V_{con}	Output of buck-boost converter
D	Duty ratio of converter
P_g	Active Power of utility grid

Q_g	Reactive power of utility grid
θ	Grid voltage phase angle
e_a, e_b, e_c	Grid side voltage
v_a, v_b, v_c	Converter terminal voltage
i_q	Grid current quadrature axis component
i_d	Grid current direct axis component
$K_{pV_{DC}}$	Proportional gain of DC voltage regulator
$K_{iV_{DC}}$	Integral gain of DC voltage regulator

CHAPTER 1

INTRODUCTION

1.1 Background of Wind Power System

Before few years, most of the research in power sector was carried out on the development of non-renewable energy based power production. But due to the depletion of industrial fuels like international oil crisis and environmental pollution effect etc the use of renewable energy sources like wind, solar, tidal is continuously improving as they are easily available in the nature. Some more reasons include advantages like they are non-pollutant, non-toxic and recyclable. From these wind energy is arising energy resource among world's top growing resources. With the eco-friendly nature of these sources energy conversion can be carried out using wind turbines. One of the main advantage of these energy sources are that they can used for small scale power generation hence it can be easily implemented in isolated areas where grid connection is practically not feasible.

This power production process faces many challenges like the structure of turbine for better efficiency and cost, control of turbine of generator for maximum power, mode of operation and some power quality problems etc. The turbines operation is possible in both the fixed speed and variable speed mode but mostly manufactures are opting for variable speed turbines by opting either turbine side control mechanism or machine side control operation. Wind power system can be used for either stand-alone or grid-connected operation according to requirement. Different types of generator topologies can be used for the power generation from turbine. The power electronic converters are very much effective or efficient enough for connecting these sources of energy and utility grid. They behave as an interface between these two.

The current work focuses on wind power production in grid-connected mode. A wind power system consisting a wind turbine, gear box, generator, and AC-DC uncontrolled converter. In this case a PMSG is used for some of its own advantages. A PMSG uses a permanent magnet for its excitation; we need not use any field circuit hence the field circuit losses are not there so its efficiency is more than other synchronous generators.

The rectifier is only used for the conversion of the AC power from generator to DC as the control is easy. If it is AC then we could have used only cycloconverter or AC voltage controller for voltage and frequency control. But using this control will not be that easy and power factor cannot be controlled. Hence we are opting for DC-DC converter control. As maximum power can be tracked only at a particular rotor speed hence a maximum power point tracker is designed to track maximum power.

The entire system is then connected to the inverter for grid connected application. The inverter is designed to operate in such a way that whatever may be the speed of the wind the output of inverter is always same as the grid voltage and grid frequency. Regulation of dc voltage of converter is done to get grid voltage synchronization and for frequency PLL circuit is required, and here we can obtain a reduction in harmonics using this controller. A battery storage system can be designed to operate the wind power system for small scale power generation. This storage system consists of a bidirectional converter which allows power flow in both the direction.

1.2 Literature Review

- ❖ The wind turbine basics and generators used for turbine and other characteristics of wind turbine are given in detail in [7].
- ❖ From [8] the mechanical aspect of turbine, various turbine configurations and wind firm topologies have been studied.
- ❖ From [2] one method for extraction of maximum power from the turbine is studied using wind generator optimum power Vs the rotating-speed curve which measures the wind generator output power and target speed of rotor for maximum power production is found from wind generator optimum power-speed characteristics.
- ❖ In [3] a Sensorless approach for MPPT has been adopted by using the dc voltage and current in optimum point. But it may require system parameters, the determination of which is not that accurate.
- ❖ A technique to track maximum power using wind generator voltage and current by calculating power from it is given in [1] and different other methods for maximum power tracking are given in [11]-[13].

- In [5] the power mapping technique has been used which uses maximum power Vs dc voltage (output of rectifier) characteristic. Here the power and voltage will increase till the intersection between them is reached.
- In [4] a method to coerce optimum power from the turbine and then feeding the power to ac grid has been recommended.
- [9], [10] explains the voltage oriented control of vector control. Vector control of three phase machine drives have been studied in detail.
- Method to connect the system to grid and design converter for grid synchronization has been studied from [13]-[18]. Here the grid interconnection of a wind turbine driven PMSG with harmonics reduction and reactive power compensation is given and in [18] a modified PLL is used where an integrator is used in lag structure rather than a conventional one.

1.3 Research Motivation

Generation of eco friendly power has become most important for researchers in the study of electric power generation. The depletion of fossil fuels has also assisted to switching to renewable, clean energy sources such as tidal energy, solar energy and wind energy. India scored 5th rank with an installed capacity of 23,444MW wind power and in 2009-2010 the rate of growth was highest among the top 4 countries. If the wind energy is captured in better way then it will be able to solve problems regarding availability of fossil fuel and environmental pollution. The power electronic converters are very important and efficient enough for connecting the non conventional energy sources to the utility grid. But there are few problems related to wind power generation like its control, power quality, topology of turbine etc. Hence to overcome these problems here a PMSG is used to get more efficiency and for small scale power generation it is very helpful as it does not require gear box, field winding. Using a DC-DC converter we are controlling the turbine to track maximum power from it. Here we have opted for a Sensorless technique for coercing optimum power where the knowledge power-speed curve is not required.

1.4 Objectives of the Project

The objective of this work is the implementation of a wind power generation system for connecting it to the utility grid. The objectives in detail are as follows:

- To study and model a basic wind turbine
- Study of different wind turbine characteristics like power versus turbine speed and wind speed and other characteristics.
- To study and analyze machine side converter (MPPT) control scheme of wind turbine irrespective of speed changes.
- Analyzing the grid side converter control scheme for synchronization with grid and reduction in harmonics of grid current.
- Implementation of the total grid connected wind power system.

1.5 Thesis Outline

This thesis consists of 6 chapters. Among them the first chapter introduces the basics of the project.

- **Chapter 2** focuses on the basic function, modeling of a wind turbine along with some of the generator topologies used for wind power generation and various turbine controls schemes are discussed.
- **Chapter 3** is about the working and design of machine side converter used to track maximum power.
- **Chapter 4** discussed about the modeling of a grid side converter control system and its working in detail for connecting the wind turbine to A.C. grid.
- **Chapter 5** includes all the simulated results which are done in the entire work and discussed the results.
- **Chapter 6** concludes the project with the scope for its future work.

CHAPTER 2

WIND POWER SYSTEM

2.1 Introduction

2.2 Sources

2.3 System Configuration

2.4 Wind Turbine

2.5 Modeling Of Wind Turbine

2.6 Wind Turbine Control System

2.7 Generator

2.8 Conclusion

2.1 Introduction

In this chapter a detailed basics regarding wind turbine is discussed. It deals with different turbine structure and their merits and demerits and some of the control mechanism of the turbine which are used most often. The turbine is expressed mathematically using its mathematical equations as we cannot use turbines directly for our research work. The mathematical analysis is discussed here.

2.2 Sources

Wind is result of movement of atmospheric air which occurs when hot air from tropical region flows towards poles whereas the cooler one from poles flows towards the tropical region. Local winds are created due to difference in air pressure which results due to change in temperature between the sea and land. While morning the wind blows from sea towards land as the land heats up rapidly. But during night the direction is opposite as water cools slower than landmass.

2.3 System Configuration

Wind is basically the movement of air which has some kinetic energy which can be extracted using turbine. The turbine shaft is coupled to the generator for conversion of the mechanical energy of the turbine to electrical one.

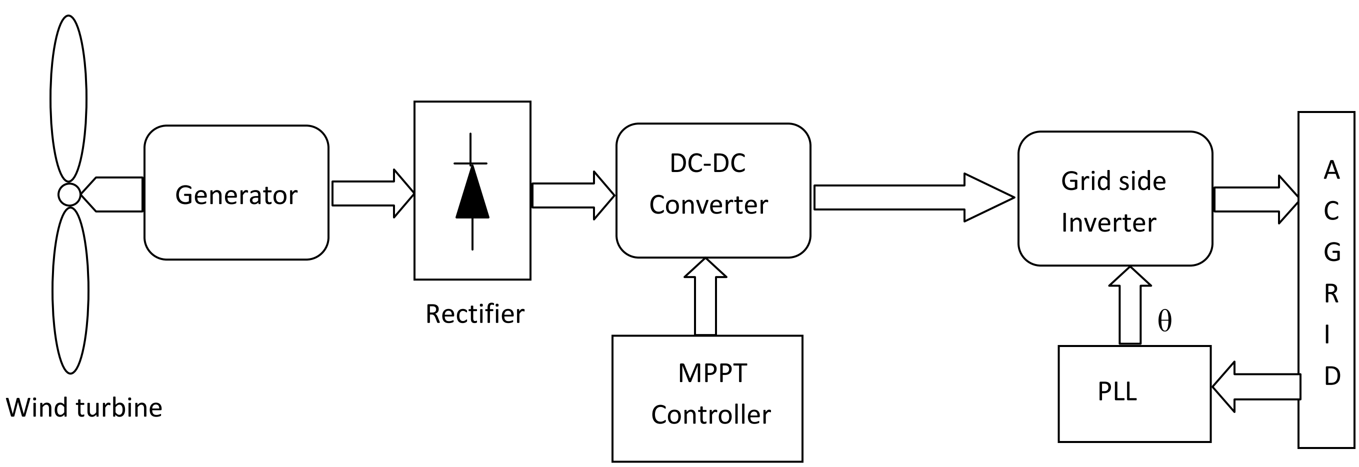

Fig.2.1 Overall block diagram of Wind power system

It contains a wind turbine coupled to a generator where the generator used can be synchronous or asynchronous depends on the application required. Maximum power can be tracked using a DC-DC converter which can be of any non-isolated type(buck, boost or buck boost). Maximization of power is done by varying duty cycle of converter and for grid synchronization we need a converter whose switching is controlled for keeping the frequency fixed and voltage is fixed by regulating dc voltage of the DC-DC converter output.

2.4 Wind Turbine

Basically it constitutes a set of blades rotating around a hub. The basic structure of a horizontal axis turbine is shown in the figure 2.3 shown below.

2.4.1 Classification Based On Structure

Depending on the structure these turbines are basically divided into two types.

- Horizontal Axis type
- Vertical Axis type

Horizontal	*Vertical*
Rotational axis is parallel to the wind direction	Axis of rotation for this type of turbine is vertical
Higher installation cost and maintenance is difficult	Installation cost is less and maintenance is easy
Higher wind energy conversion efficiency	lower energy conversion efficiency
High tower has access to stronger wind	Torque fluctuations are more and prone to mechanical vibrations
Most widely used due to high efficiency	Not used in large scale due to less efficiency

Table: 2.2 Comparison among horizontal and vertical type turbine

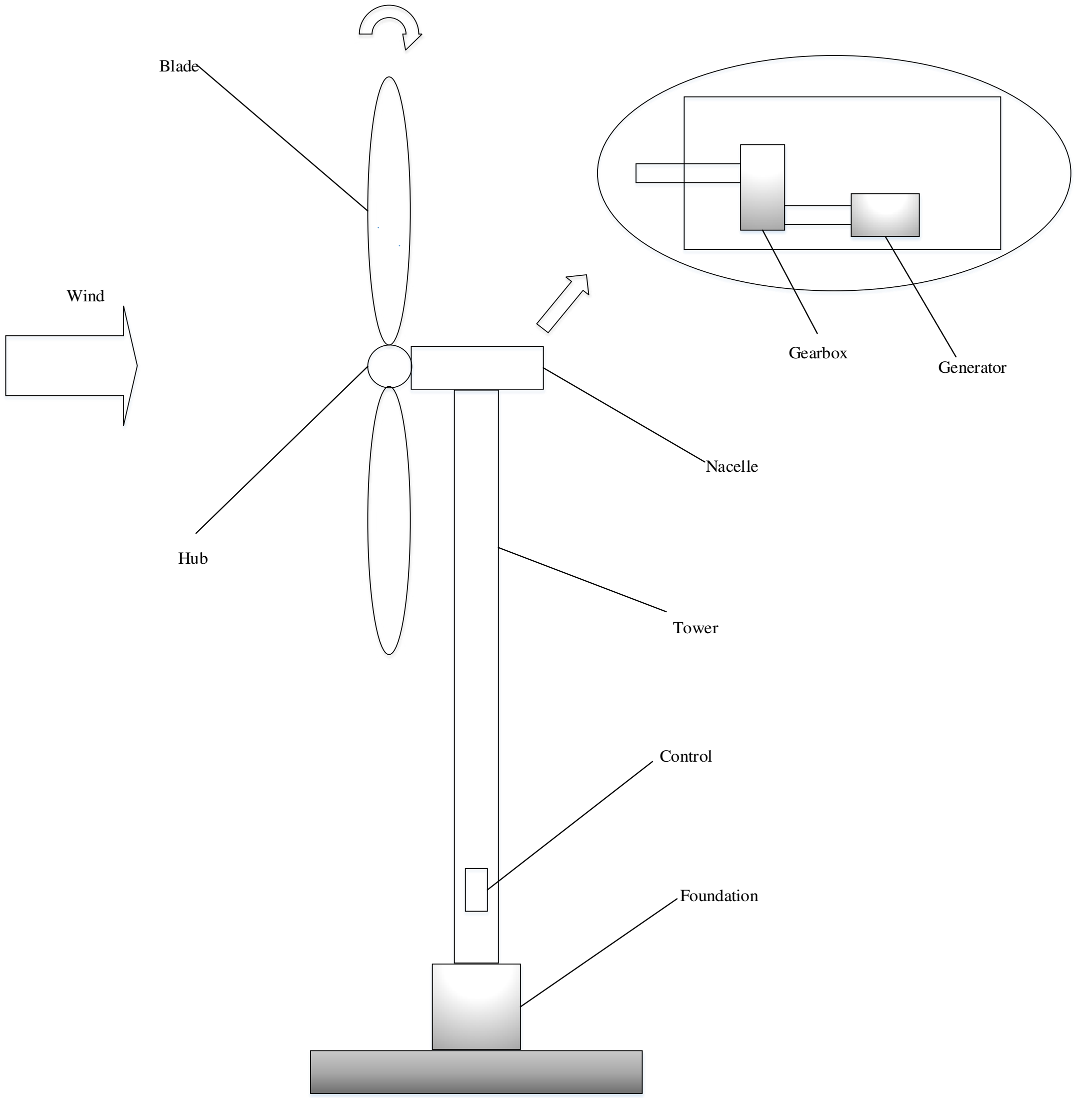

Fig. 2.3 A horizontal axis wind turbine

2.4.2 Classification Based On Speed

According to the function again these turbines can be categorized into 2 types:

- Fixed speed wind turbine(FSWT)
- Variable speed wind turbine(VSWT)

FSWT	***VSWT***
Rotates almost at constant speed, determined by the frequency of grid, and pole pairs of the machine.	Rotational speed is adjusted continuously in accordance to the speed of wind.
Reliable, Simple, low cost ,robust, and less maintenance	Complex control system and costly and more losses as converters are used here.
Conversion efficiency of wind energy is lower	Higher wind energy conversion efficiency.
Mechanical stress is high and bad power quality as maximum efficiency is obtained at a particular wind speed	With better quality of power and reduction in mechanical stress.

Table: 2.3 Comparisons between FSWT and VSWT

2.5 Modeling of Wind Turbines

Wind is the movement of air, which has a kinetic energy. The aerodynamic power of the wind which is in the form of K.E. is captured by the turbine and shaft of turbine is attached to the generator which will convert the mechanical energy output of turbine to electrical form.

Total power captured by the turbine can be written as follows:

$$P = \frac{1}{2}\rho A V^3 C_p$$

The total wind power of the wind cannot be captured using turbine. The ratio of the power captured by the turbine to the total power is dimensionless. The maximum value of this ratio lies between 0.4-0.5 which is different for different turbines. This ratio is known as coefficient of power (C_p) which will determine the power captured by turbine from wind.

The value of C_p is related to the pitch angle (β) and tip speed ratio (λ) of turbine which is given later.

Tip-Speed Ratio:

TSR is the tangential speed (i.e. the rate of turning of the ends of the blade of a turbine) of a wind turbine when compared to the speed of the wind.

TSR (Tip speed ratio) can be expressed as

$$\lambda = \frac{\Omega R}{V}$$

The equation of C_p for the turbine used here is as follows:

$$C_p(\lambda, \beta) = 0.5176\left(\frac{116}{\lambda_i} - 0.4\beta - 5\right)e^{\frac{-21}{\lambda_i}} + 0.0068\lambda_i$$

Where,

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

Here,

P– Power captured by wind turbine

ρ –Air density

β –Pitch angle (degrees)

A– Area covered by the turbine blades (m^2)

V–Speed of wind (m/s)

C_p–Coefficient of power of the turbine

λ –Tip speed ratio

Ω-Angular velocity of the turbine in rad/sec

R-Radius of blades of turbine

2.6 Wind Turbine Control System

Due to change in environmental conditions the wind speed always varies with varying wind directions also. But we need to extract the maximum power from wind for optimum conversion efficiency. Hence to get that various control schemes are used. These may include turbine side or generator side control.

Some of them are as follows:

- Pitch angle control
- Stall mode control
- Yaw control
- Power electronic Control

2.6.1 Pitch Angle Control

Here the pitch angle of the turbine varies in accordance to the wind speed to get maximum efficiency at different wind speed.

2.6.2 Stall Control

This control scheme is used during high wind speed. During high speed the blade of the turbine is rotated some degrees in the direction opposite to pitch angle control. Using this we can obtain constant rated wind power when wind speed is above rated wind speed i.e. up to the furling speed of turbine.

2.6.3 Yaw Control

This method is useful whenever the wind flow direction changes. The turbine is tilted to get optimum power during a change in the direction of wind. Tail vane is used in small turbines and yaw motor is used for large turbines in wind power generation.

2.6.4 Power Electronic Control

Here we need not to do any changes with the turbine blade positions. The electrical load is varied using power electronic controllers and using MPPT theorem the speed of rotor of generator is automatically adjusted to track maximum power. No mechanical control scheme is used here. In this work we have used power electronic control scheme.

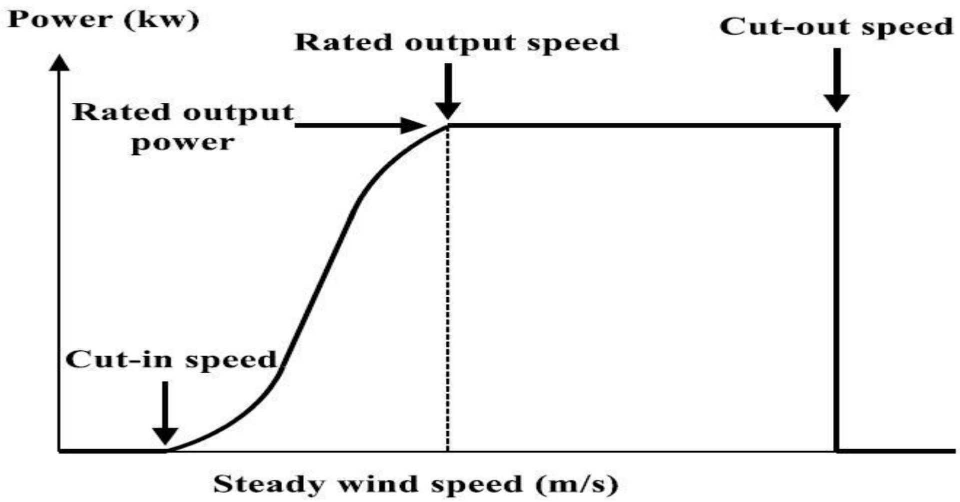

Fig. 2.5 Power Versus wind speed characteristic

2.7 Generator

The shaft of the wind turbine is coupled mechanically to shaft of the rotor of the generator, so that the mechanical power output of the turbine which is transmitted to the rotor shaft and according to Faraday's law of electromagnetic induction whenever a conductor is mover inside rotating magnetic field or vice versa then e.m.f. is induced in the conductor and current starts flowing through the conductor according to generator principle.

2.7.1 Types of Generator

We can classify generators as alternating or direct current depending on the output current. Generally the output of all generators is alternating but if we will connect one commutator in the A.C. generator then it will behave as D.C. generator.

Another classification of generators can also be done according to the rotation of the rotor.

- Synchronous generators (constant speed): These generators will run at a constant speed depending upon the no of poles and applied frequency.

- Asynchronous generators (variable speed): These generators are never operated at synchronous speed if so then no torque will be produced and they won't be able to rotate. They are operated above synchronous speed for generator action.

Another way of classifying synchronous generators is based on the magnetic field.

For generator action we need a magnetic field which may be a permanent magnet or electromagnet. Here we have used one permanent magnet synchronous generator to avoid the supply requirement for the excitation of field as the magnetic field is produced by using a permanent magnet.

Induction generators are asynchronous generators and these are not self exciting type. There are basically three types of induction generators.

- Singly Fed Induction Generator: In this case the excitation is given to stator and rotor may be short circuited or it may consist of winding depending on the rotor structure.
- Doubly Fed Induction Generator: when a squirrel cage rotor IG is fed from stator and the rotor side then it is called as DFIG.
- Self Excited induction generator (SEIG): Induction generators can be used in self-excitation mode also by taking reactive power from a capacitor bank.

2.7.2 Permanent Magnet Synchronous Generator (PMSG):

In PMSG permanent magnets are used to obtain the magnetic field. Here we need not to use any external supply to excite field winding. Field winding is also not required as magnetization is provided by using permanent magnet rather than electromagnet. The field flux cannot be controlled it is constant throughout. Remaining things are similar to a synchronous generator.

We are using PMSG in our work because of some of its advantages listed below:

- Small size, less weight, high energy density
- Less copper loss leads to more efficiency as field winding is not present.

- Can couple the generator directly to the turbine without gear box(Can be used with more number of poles hence its operating speed will be less hence no gear box is needed which leads to less weight of turbine)
- No need of excitation current
- Can handle a wide range of rotor speed

Some of the disadvantages of PMSG are as follows:

- Large PMSG are very costly restricting economic rating of machine
- Non controllable air gap flux so the voltage of the machine cannot be easily regulated.

The EMF equation of a synchronous generator can be written as:

$$E = 4.44\, f\, \phi\, T$$

Where,

Φ - Average value of flux

f -frequency of supply

T -number of turns per phase

2.8 Conclusion

This chapter concludes with the discussion of different turbine topologies, modeling of turbine, different types of generator which can be used with the wind turbine and their advantages and disadvantages. The turbine used here is driven by a PMSG for its advantages as low cost, reliability, efficiency etc. The wind generator is then controlled by a machine side controller to track maximum power from turbine. These machine side converter is studied in detail is the chapter 3.

CHAPTER 3

MACHINE SIDE CONVERTER CONTROL

3.1 Introduction

This portion deals with the design of a control mechanism to coerce the optimum power from the wind generator by operating the generator at its optimum speed. The system constitutes a rectifier with a buck-boost converter whose duty cycle will be varied to coerce the maximum power from the turbine. The process of coercing the maximum power is described thoroughly in this chapter, and it also discussed some of the converter topologies.

3.2 Maximum Power Point Tracking

It refers to a control system which is used to track the optimum power from a wind turbine for different wind speed. These techniques are primarily of two types for a wind turbine i.e. either from turbine side by using mechanical sensors or from generator side by using power electronic equipment. Using power electronic equipment by varying the operating speed of the generator we will be able to track maximum power from the turbine.

3.2.1 Necessity of MPPT

From fig 3.1 we can clearly observe that the power output of the wind generator is dependent on wind generator speed. From the curve we can see that for every wind speed at a particular value of W/G speed the power tracked will be maximum. From fig 3.2 we can find that coefficient of power will have its maximum point at a particular value of TSR that we can get from the curve itself and by operating the wind generator at its optimum speed we can get optimum TSR and the optimum power. We are going for this MPPT control algorithm to enhance the efficiency of the turbine.

3.3 MPPT of Wind Generator

The optimal power line for different wind speed will be obtained at different generator speed. Hence to track optimum power we have to operate the wind generator at optimum speed at which it will track maximum power, and it should follow the optimum power line as shown in fig 3.1.

The maximum power will be obtained when:

$$\frac{dP}{d\Omega} = 0$$

$$\frac{dP}{d\Omega} = \frac{dP}{dD} \times \frac{dD}{dV_R} \times \frac{dV_R}{d\Omega_e} \times \frac{d\Omega_e}{d\Omega}$$

For buck-boost converters

$$V_{con} = \frac{D}{1-D} V_R$$

Where,

P– Wind power

Ω– Rotor speed of generator

p– Number of pair of poles in the generator

V_R– Rectifier output voltage or input to dc-dc converter

Ω_e – Generator- phase voltage angular speed.

V_{con} –Output of buck-boost converter

D– Duty cycle of converter

By differentiating the voltage equation of dc-dc converter we get

$$\frac{dD}{dV_R} = -\frac{D^2}{V_{con}} \neq 0$$

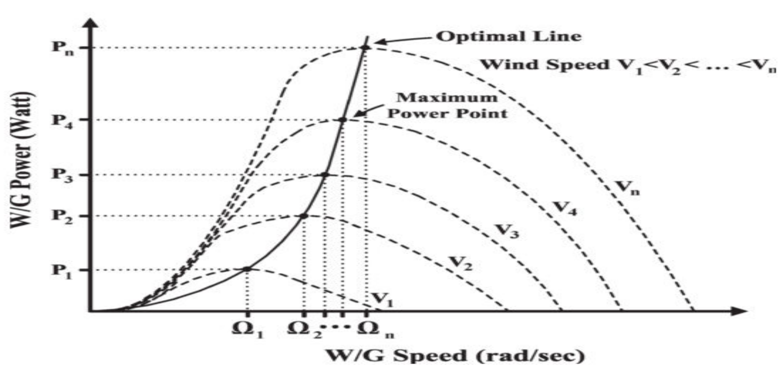

Fig. 3.1 Power versus Speed Characteristic of WG

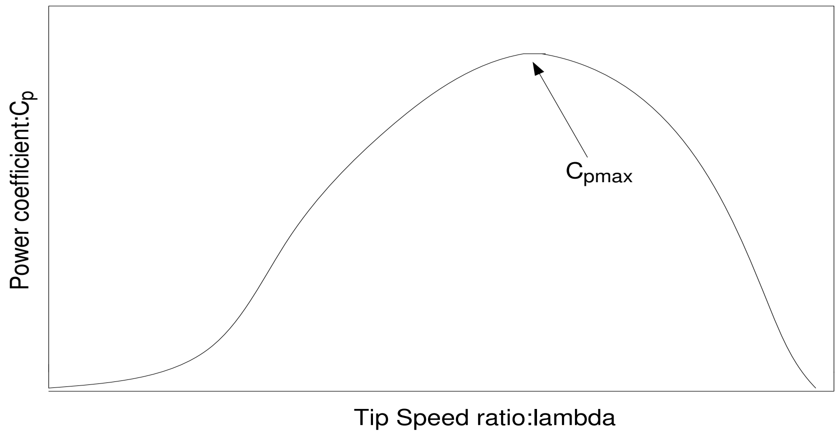

Fig. 3.2 Characteristic of coefficient of power versus TSR

From the above equation it is clear that $\frac{dD}{dV_W}$ is having negative and nonzero value.

The speed of rotor of the wind turbine and angular speed of generator-phase voltage can be related by the equation as follows:

$$\Omega_e = p \cdot \Omega$$

$$\frac{d\Omega_e}{d\Omega} = p > 0$$

$\frac{d\Omega_e}{d\Omega}$ is positive and non-zero.

The generator output voltage and output voltage of the rectifier are directly proportional to each other.

The emf equation of generator can be given as follows:

$$E = 4.44\, f\, \phi\, T$$

As, $E \propto V_R$ and $f \propto \Omega e$

So $\frac{dE}{d\Omega_e} > 0$

From the above equations we found that $\frac{dD}{dV_R}$, $\frac{d\Omega_e}{d\Omega}$ and $\frac{dV_R}{d\Omega_e}$ are non-zero values.

So $\frac{dP}{d\Omega} = 0$ is possible when $\frac{dP}{dD} = 0$.

Hence from the above analysis we conclude that by varying duty ratio of the converter the tracking of maximum power can be done.

The total MPPT process has been shown in the figure 3.3 as shown below.

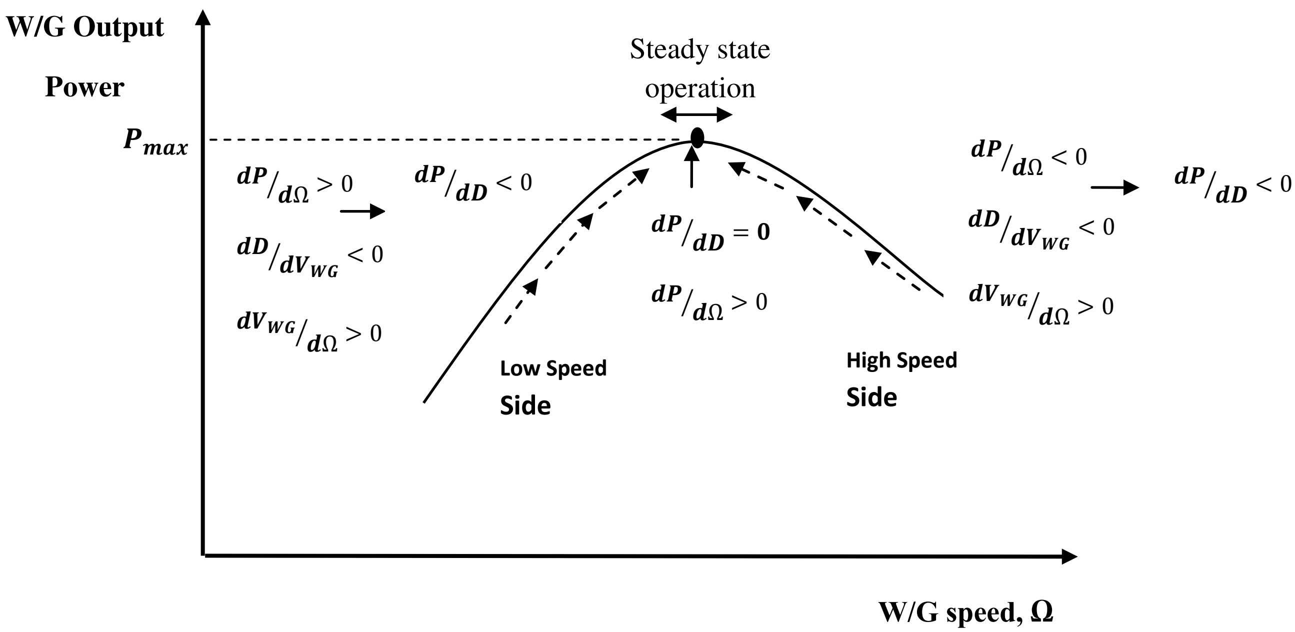

Fig. 3.3 MPPT Process of WG

The adjustment of duty-ratio traverses in the direction of $\frac{dP}{dD}$ and duty-ratio value increases on the high-wind speed side of the wind generator characteristic, with a result of reduction in speed of wind generator rotor and increase in power till the MPP is reached.

In the same way on low-speed side of rotor of the wind generator duty cycle will be reduced which results in the increment of the generator speed rotor and increase in power till maximum power is reached.

For MPPT we can use any type of DC-DC converter as per load requirement, supply availability and by changing alternative DC-DC converter configurations such as cuk, flyback, boost and buck we can also track maximum power.

3.4 DC-DC Converter

A DC-DC converter transforms a dc voltage from one level to another level. Its works in the same way as that of a transformer for a.c. applications. It may be used to increase the voltage or decrease the voltage level. This control action can be obtained by varying the duty ratio of the converter.

Some of the basic converter types are listed below.

- Buck converter
- Boost converter
- Buck-Boost converter

3.4.1 Buck Converter

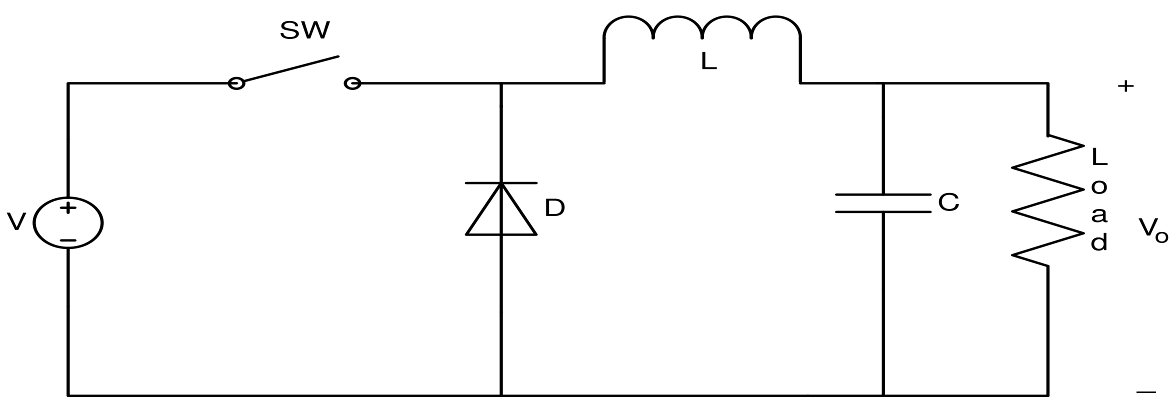

Fig. 3.4 Circuit diagram of a simple buck converter

Above figure shows the circuital arrangement of a buck converter. This converter is used to reduce the voltage level similar to a step-down transformer used in AC supply.

The output voltage equation of the above converter is:

$$V_o = DV_{in}$$

Where,

V_o= Converter output voltage

V_{in}= Converter input voltage

D=Duty ratio of converter

3.4.2 Boost Converter

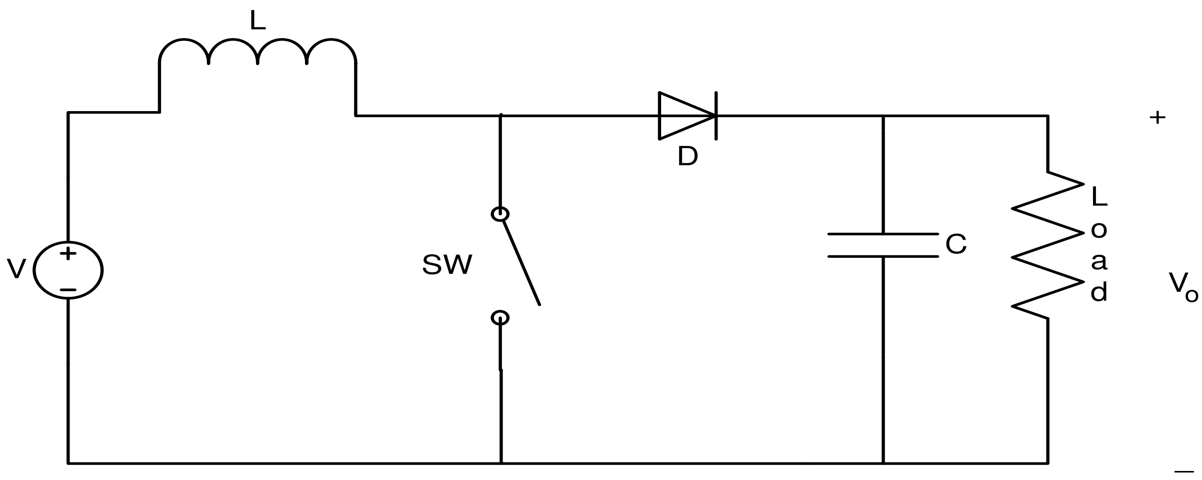

Fig. 3.5 Circuit diagram of a simple boost converter

This converter is used while enhancing the voltage profile similar to a step up transformer. The switch is connected in across the supply voltage. The output voltage equation of the converter is

$$V_o = \frac{1}{1-D} V_{in}$$

3.4.3 Buck-Boost converter

The buck-boost converter is used to obtain the output more or less than the source voltage according to the value of duty cycle.

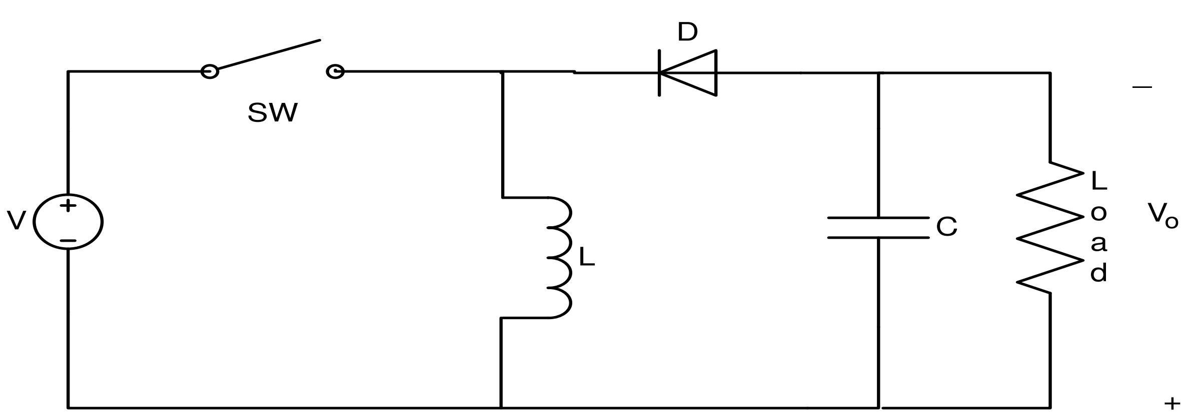

Fig. 3.6 circuit diagram of a simple buck-boost converter

The circuital arrangement of such type of converter is given in the figure 3.6 above.

The output voltage equation of this converter is

$$V_o = \left(\frac{D}{1-D}\right) V_{in}$$

Whenever the duty cycle value is more than 0.5, then it will behave as boost converter and below 0.5 it acts as buck converter. As in this case, we can get both the buck and boost operation hence we are using the above converter for our convenience in our work.

3.5 Conclusion

Here the maximum power of the wind generator is tracked by using perturb and observe method by changing the duty ratio of the dc-dc converter used. The impedance matching is done to track maximum power using MPP theorem. The next task is to connect the system to the utility grid for which a grid side converter is required which will be useful for grid synchronization. That converter operation is discussed in detail in the next chapter.

CHAPTER 4

GRID SIDE CONVERTER CONTROL

4.1 Introduction

After tracking maximum power from turbine generator set, the output of the wind generator converter set will either connected to the grid, or to battery or load for isolated operation. For connecting it to grid the voltage and frequency of the grid side converter output should be matched with the grid frequency as the grid side voltage and frequency are constant. The GSC control system is used for regulating the dc-link voltage and for injecting the generated power into utility grid. Including these, the grid-side converter is used for compensating the reactive power, and harmonics generated in currents by the non-linear loads in case load is non- linear. Here the GSC is designed in such a way that it will be operated at UPF.

The grid-side inverter is used to maintain the power balance during wind fluctuations and grid disturbances by regulating dc voltage output of the DC-DC converter.

4.2 Grid Side Converter

By regulating the d.c voltage of the converter, we can generate a control signal that will produce gate pulses for the operation of the inverter connected between the DC-DC converter and A.C. grid. This control system consists of two loops connected in cascade.

- Outer loop is the voltage control loop which is used to set the current reference for active power control.
- Inner loop is current loop which achieves harmonic reduction and reactive power compensation as per the requirement.

The implemented control system is analyzed in a synchronously rotating reference frame. In this case, the control variables behave as dc which leads to easy filtering and controlling. This control is achieved by using grid voltage oriented vector control scheme.

4.2.1 Park's Transformation

It is a mathematical transformation which rotates the reference frame at synchronous speed in a three phase system to simplify the analysis of 3 phase circuits. This transformation is used to convert a-b-c to synchronously rotating i.e. d-q reference frame. This reduces the three A.C. quantities into two D.C. quantities resulting into simplified calculations.

We can get the d-q-0 component from a-b-c by performing a α-β-0 Clark's transformation in the stationary reference frame. Then α-β-0 to d-q-0 transformation is performed in synchronously rotating reference frame.

The matrix governing Park's transformation is:

$$\begin{bmatrix} V_d \\ V_q \\ V_0 \end{bmatrix} = \frac{2}{3}\begin{bmatrix} cos(wt) & cos\left(wt - \frac{2\pi}{3}\right) & cos\left(wt + \frac{2\pi}{3}\right) \\ -sin(wt) & -sin\left(wt - \frac{2\pi}{3}\right) & -sin\left(wt + \frac{2\pi}{3}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix}\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix}$$

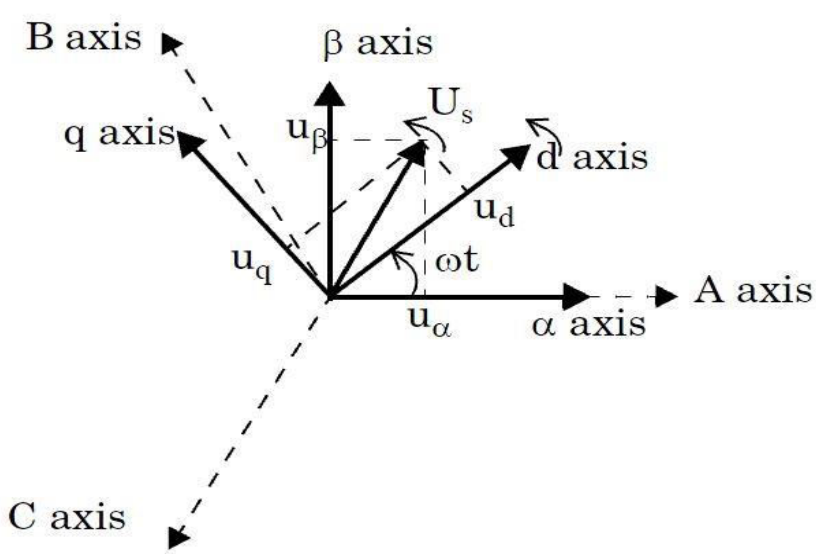

Fig. 4.2

4.3 Modeling of GSC

The circuit shown below represents a grid-side converter that is getting supply from dc voltage output of the converter and connected to 3 phase voltage source acting as a grid.

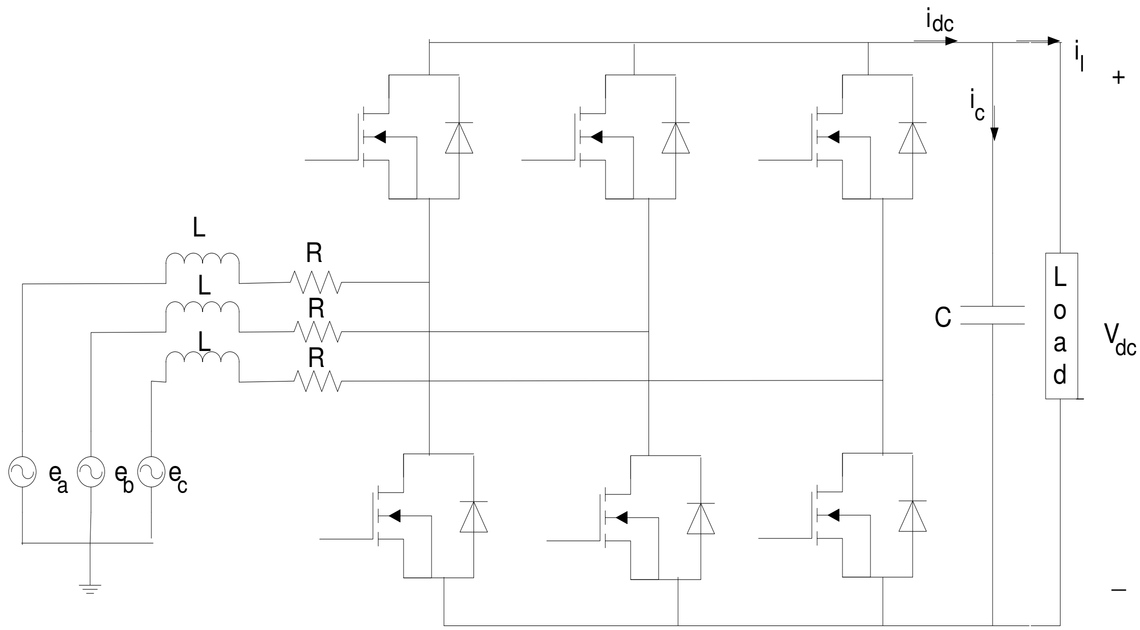

Fig. 4.3 Grid Side Converter Circuit

The grid voltage equations in a-b-c frame are given as:

$$e_a = L\frac{di_a}{dt} + v_a$$

$$e_b = L\frac{di_b}{dt} + v_b$$

$$e_c = L\frac{di_c}{dt} + v_c$$

Where:

e_a, e_b, e_c are grid side voltages.

v_a, v_b, v_c are inverter terminal voltages.

L is the coupling inductance.

After Park's transformation, the above equations are changed to the synchronous d-q frame. The grid voltages after transformation are:

$$e_d = L\frac{di_d}{dt} - wLi_q + V_d$$

$$e_q = L\frac{di_q}{dt} + wLi_d + V_q$$

The active and reactive power associated with GSC is given below.

$$P = \frac{3}{2}\left(e_d i_d + e_q i_q\right)$$

$$Q = \frac{3}{2}\left(e_q i_d - e_d i_q\right)$$

4.4 Voltage Oriented Vector Control of GSC

The design objective of the controller is that it is supposed to generate the reference currents such that grid will be able to supply the fundamental active power to load. That means the grid should have very less harmonics and it should be operated at unity power factor.

To control the GSC, here we are opting for the voltage oriented vector control scheme where voltage vector is oriented along d-axis. So e_d will be same as that of the grid voltage and $e_q = 0$.

This leads to the power equation as:

$$P_g = \frac{3}{2}(e_d i_d) \qquad\qquad Q_g = -\frac{3}{2}\left(e_d i_q\right)$$

As we need to operate the grid in UPF so for UPF operation:

$$i_q^* = 0$$

i_q^* is the reactive power component.

i_d^* is the active power component that is responsible for the exchange of active power between the WECS and the utility grid.

To control GSC we need to find reference currents in which the quadrature axis component is set to zero for UPF operation. Now we can find direct axis reference current by using a PI controller.

The total control scheme is explained in the block diagram shown below.

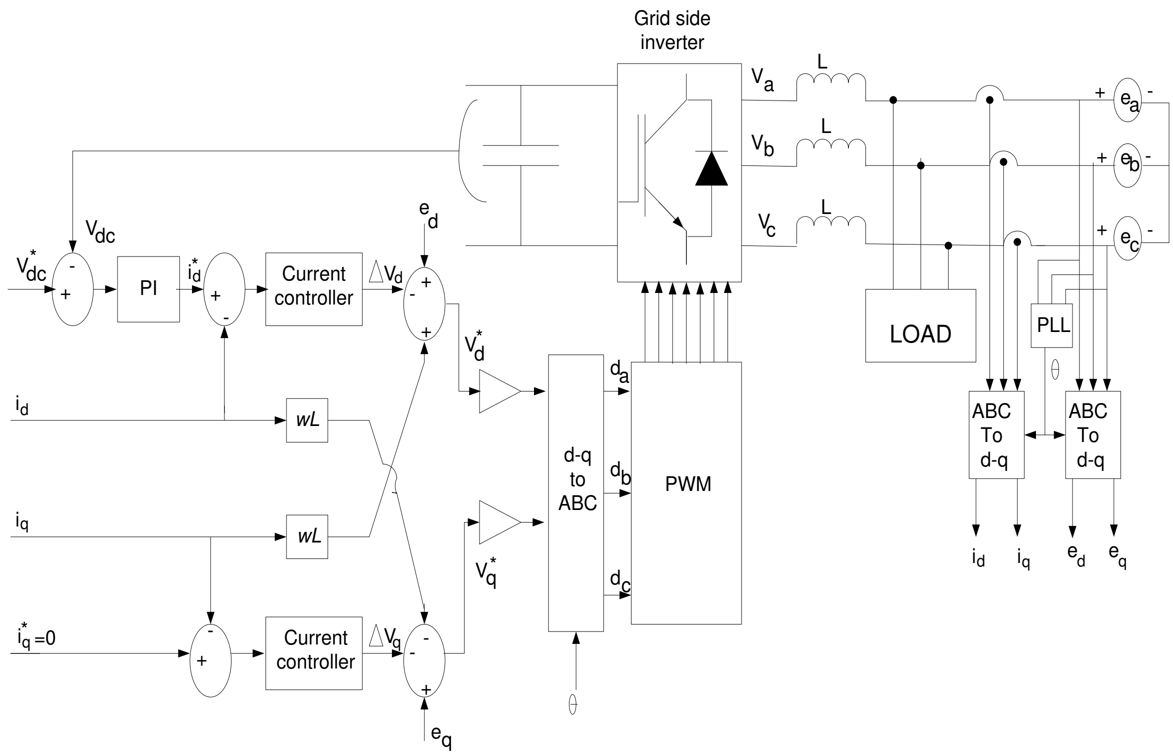

Fig. 4.4 Block diagram of GSC Control

The d-axis reference current is found from the equation below:

$$i_d^* = \left(k_{pV_{dc}} + \frac{k_{iV_{dc}}}{s}\right)(V_{dc}^* - V_{dc})$$

$k_{pV_{dc}}$=the proportional gain of voltage regulator

$k_{iV_{dc}}$=the integral gain of voltage regulator.

The PI controller used here is mostly able force the grid current for finding the reference current accurately, but due to the presence of coupling terms in the grid voltage equations in d-q frame deteriorates its performance. Hence to avoid this we need to decouple the system by presenting it as a first order linear dynamic system with better controllability.

The decoupling equations are as follows:

$$L\frac{di_d}{dt} - \Delta V_d = 0$$

$$L\frac{di_q}{dt} - \Delta V_q = 0$$

Derivation of the output signals ΔV_d,ΔV_q are done from the inner current controller loops as:

$$\Delta V_d = k_p(i_d^* - i_d) + k_i \int (i_d^* - i_d)dt$$

$$\Delta V_q = k_p\left(i_q^* - i_q\right) + k_i \int (i_q^* - i_q)dt$$

By substituting the above equations in the grid voltage equations we can get the decoupled equations as follows:

$$V_d^* = e_d + wLi_q - \Delta V_d$$

$$V_q^* = e_q - wLi_d - \Delta V_q$$

The a-b-c axis reference voltages are obtained using the reference voltages by using the grid voltage phase angle θ.

The θ value can be obtained from phase locked loop technique.

4.4.1 Phase Locked Loop Technique

In PLL technique generation of an output signal is done whose phase is related to the phase of an input signal. The phases of input and output are kept in lock step results in same input and output frequencies. Accordingly, in addition to synchronizing signals, a

PLL is used to track an input frequency, or able to produce a frequency which is a multiple of the input frequency. The input to the PLL is the grid voltage using which it will generate θ which will be used during the transformation from a-b-c to d-q and vice versa. In the figure shown below the input V_{abc} is the grid voltage which is transformed to dq form and then PLL is locked by setting the d-axis voltage as zero and then it passes through the integrator and VCO which will give us the desired output i.e. phase angle θ.

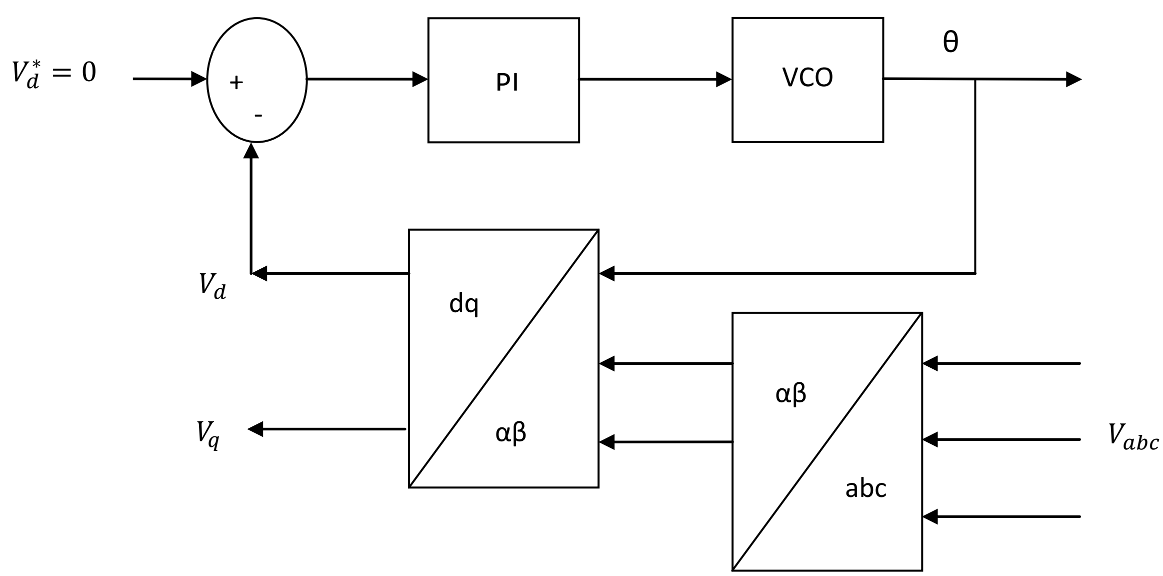

Fig. 4.5 Block diagram of three phase dq-PLL circuit

4.5 Conclusion

This section ends with the grid synchronization of the wind power generation system with the utility grid using voltage oriented vector control method. This control mechanism leads to UPF operation of the grid and the harmonics of source current is also reduced. This chapter is followed by the section where all the simulated results are listed and the results are discussed in detail.

CHAPTER 5

SIMULATION RESULTS AND DISCUSSION

5.1 Introduction

5.2 Results of wind generator

5.3 Results after MPPT

5.4 Results of Gird side converter control

5.5 Conclusion

5.1 Introduction

This section shows all the results that are obtained after simulating the system in MATLAB. Simulink is used for simulating the total system. The specifications of the generator and the turbine are given in the appendix.

5.2 Results of Wind Generator

Fig 5.1 shows the wind turbine power characteristics at various wind speed. The specifications of the PMSG and the turbine used here are:

Base Speed of turbine: 10m/s

Blade Radius: 1m

Rated Power of generator: 2500VA

Rated Voltage: 170V (RMS line-line)

Rated Frequency: 50Hz

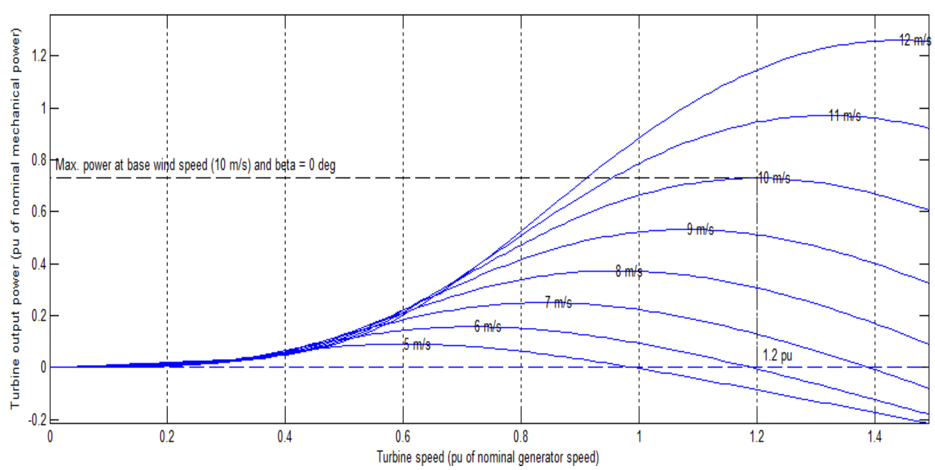

Fig. 5.1 Wind Turbine Power characteristics (pitch angle beta=0°)

Fig 5.2 represents the rotor speed of the generator when the speed of the wind is 10m/s which is the base speed of the turbine. The output of the PMSG is shown in fig 5.3.After implementing the maximum power point tracker, the point of operation of peak power of wind generator output is traced which are shown in the fig 5.6-fig 5.8 given below.

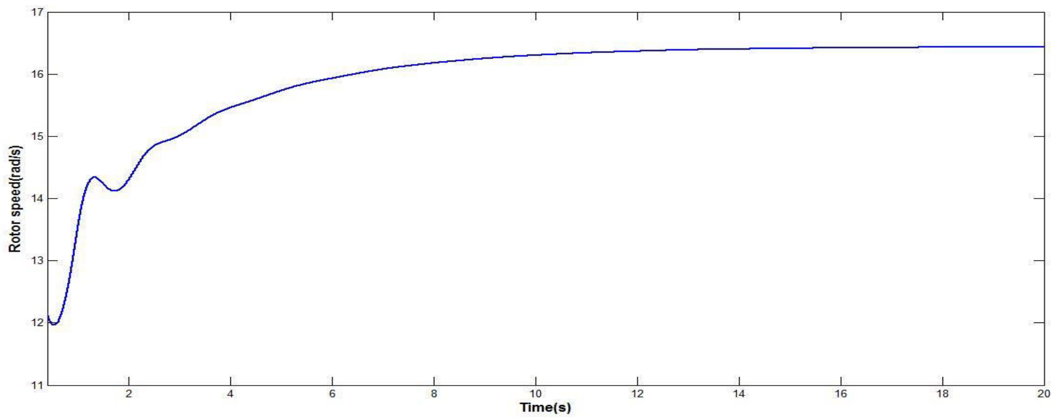

Fig. 5.2 Rotor speed of generator

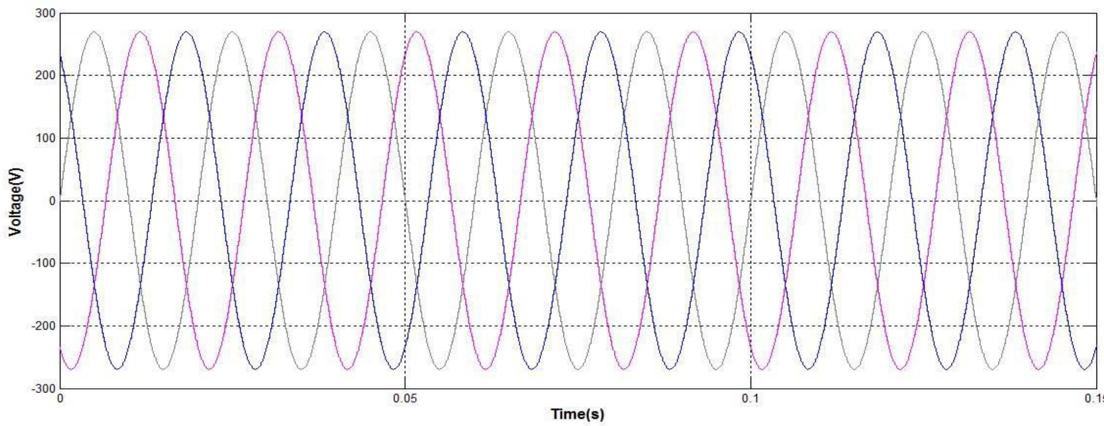

Fig. 5.3 Three phase line voltage output of PMSG

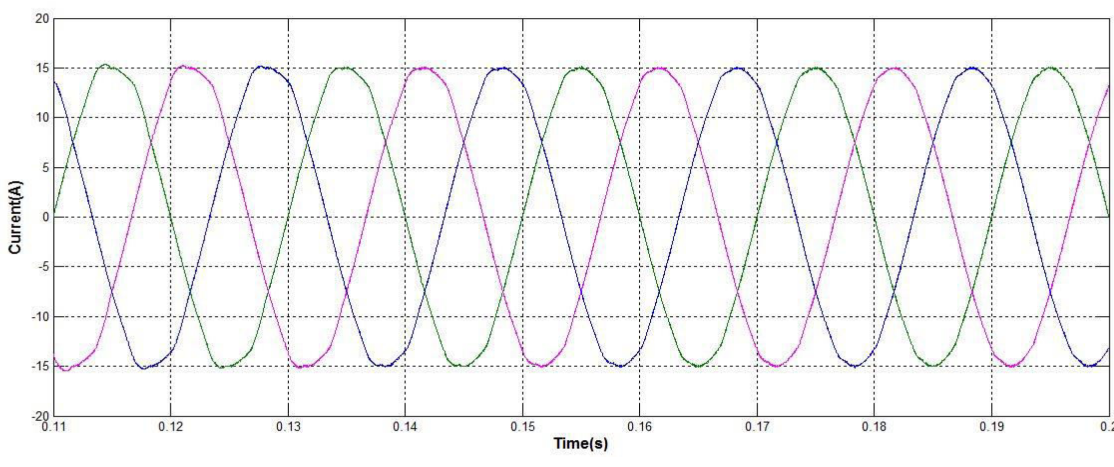

Fig. 5.4 Three phase stator current output of PMSG

5.3 Results after MPPT

The output voltage of the buck-boost converter at which maximum power is traced is given in the figure 5.6 shown below. Consequently the current and the maximum power values are given by the turbine are shown in the fig 5.7 and fig 5.8 respectively. The converter used here is having the specification:

Forward voltage drop of IGBT=2.5V

Forward voltage drop of diode=0.8V

Value of inductor= 47×10^{-6}H

Value of capacitor=2000$\times 10^{-6}$F

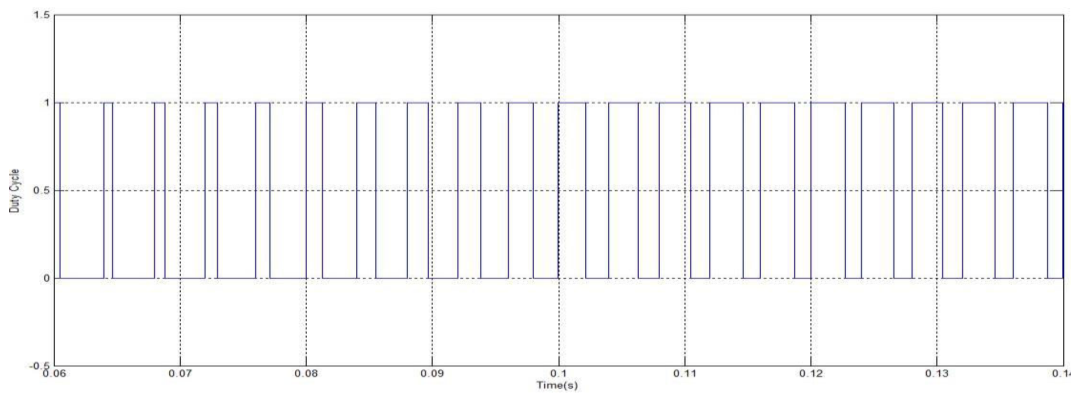

Fig. 5.5 Duty cycle of DC-DC Converter

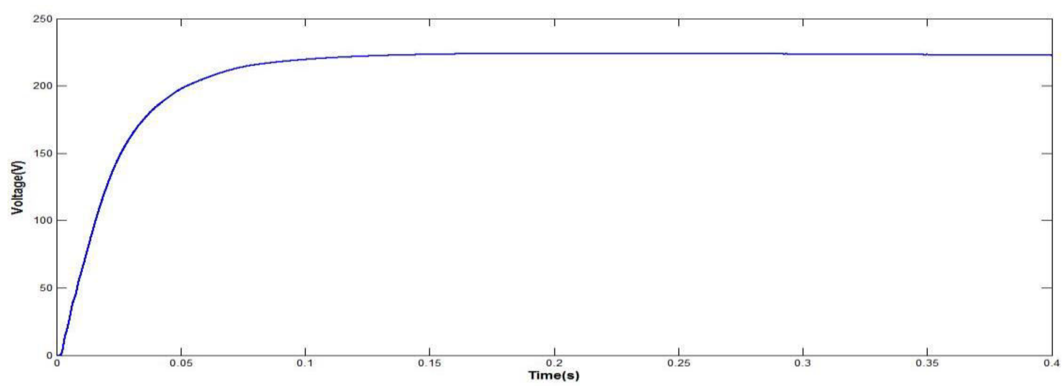

Fig. 5.6 Output Voltage of DC-DC Converter

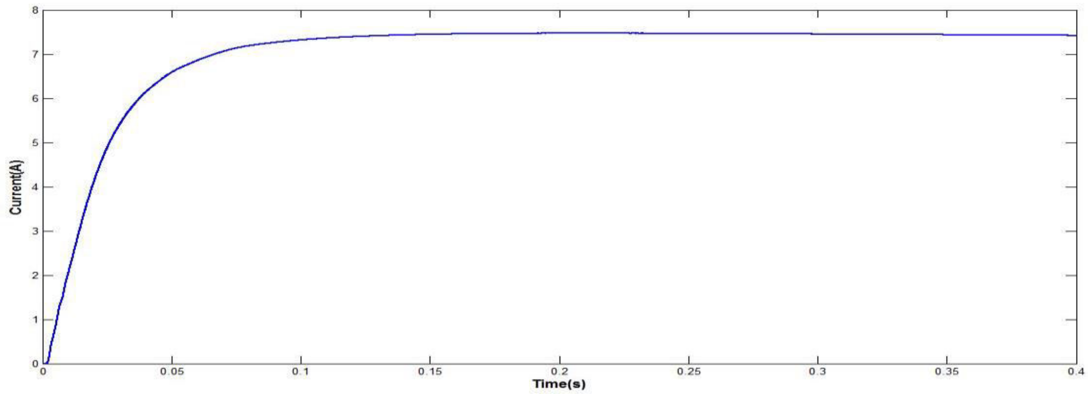

Fig. 5.7 Output Current of DC-DC Converter

In the above converter we got the maximum power when the converter output voltage is around 235V and the current is about 7.5A. The maximum power point which we obtained is nearly 1763W when the wind speed is 10 m/s.

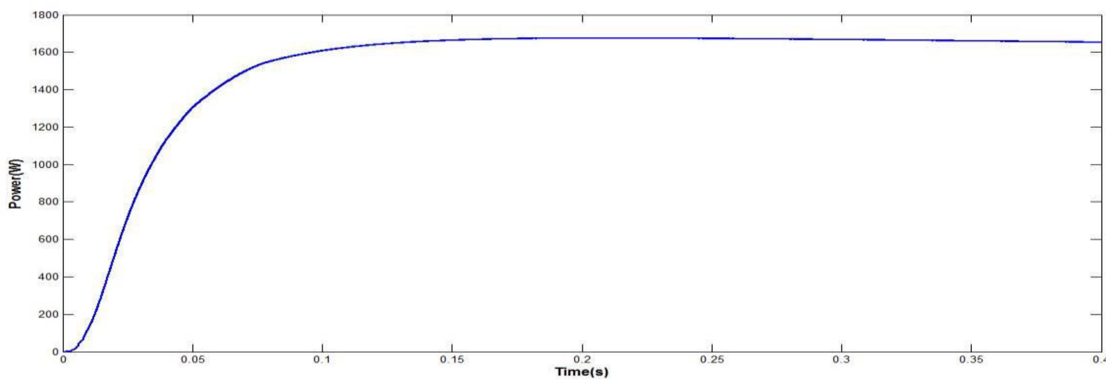

Fig. 5.8 Output power of DC-DC Converter

5.4 Results of Grid Side Converter Control

Figure 5.9 shows the output voltage of the VS-PWM inverter which is connected to the grid. The specifications of the grid are:

Grid base Power=1800W

Grid RMS voltage= 170V

DC link Voltage=240V

DC Capacitor=1.5mF

Coupling Inductor=1mH

Non linear Load (Bridge rectifier with RL-load) =10Ω, 200mH

Grid frequency=50Hz

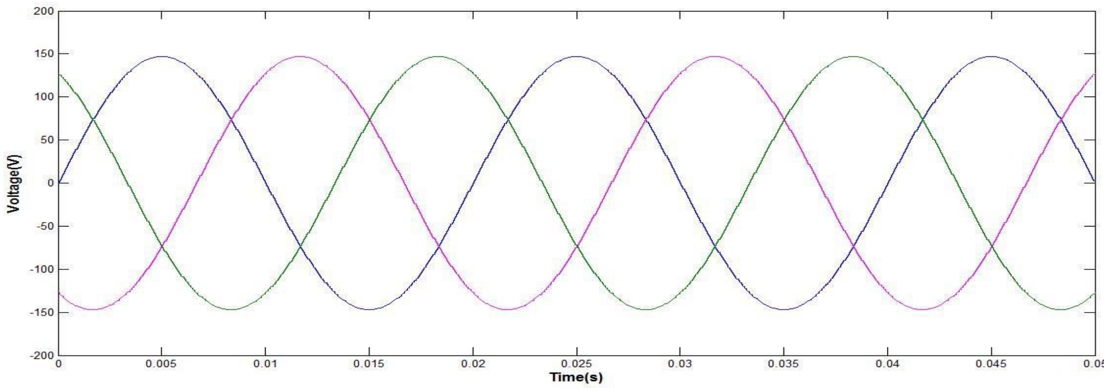

Fig. 5.9 Output phase voltage of the GSC

The grids current and load currents using the GSC are given below in figures 5.10-5.13 with their THD content.

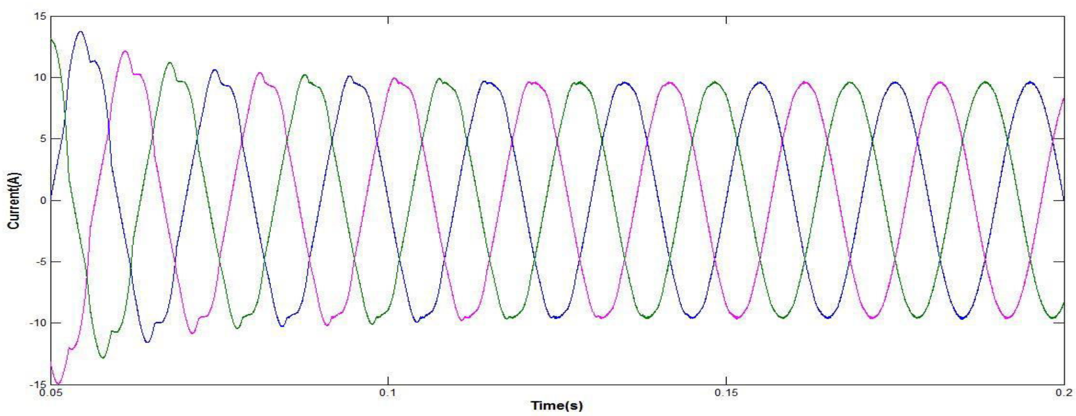

Fig. 5.10 Grid Current after harmonic mitigation

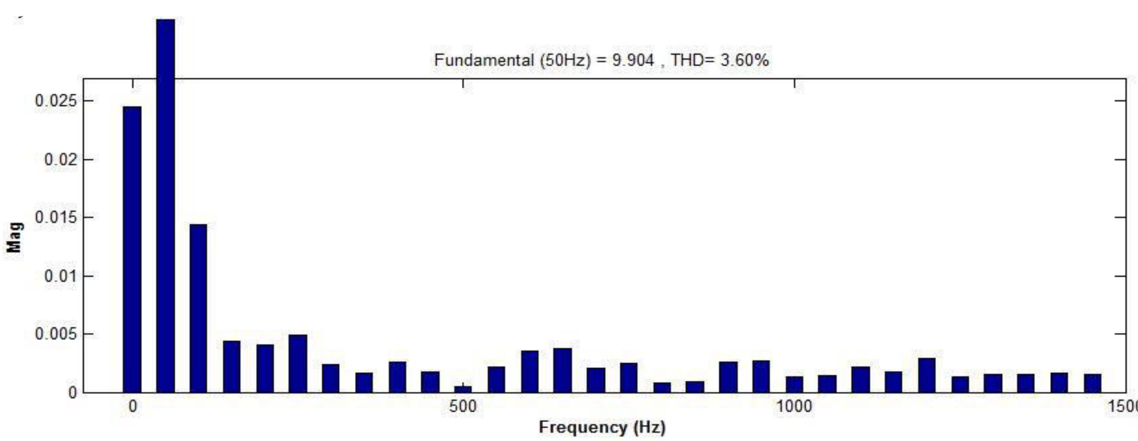

Fig. 5.11 THD of Grid current

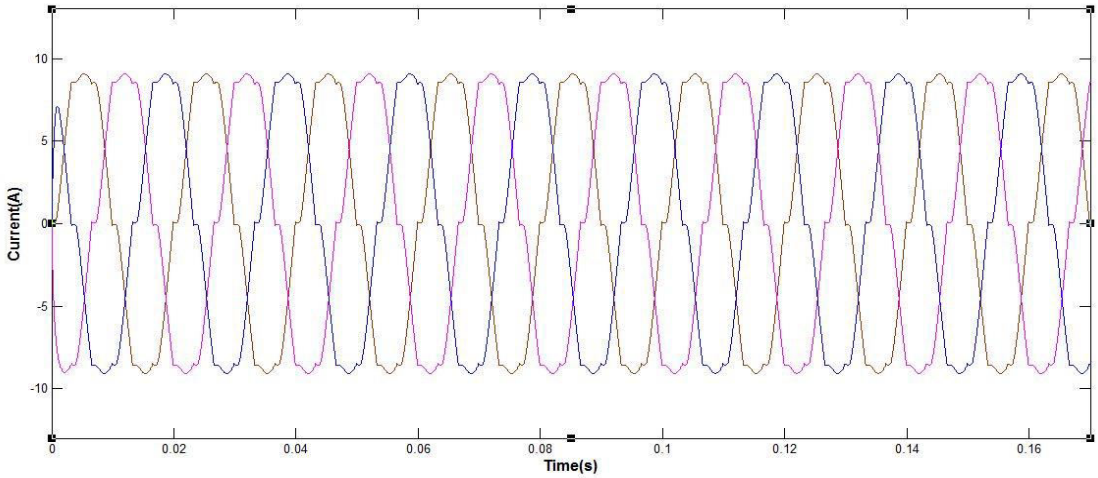

Fig: 5.12 Load current

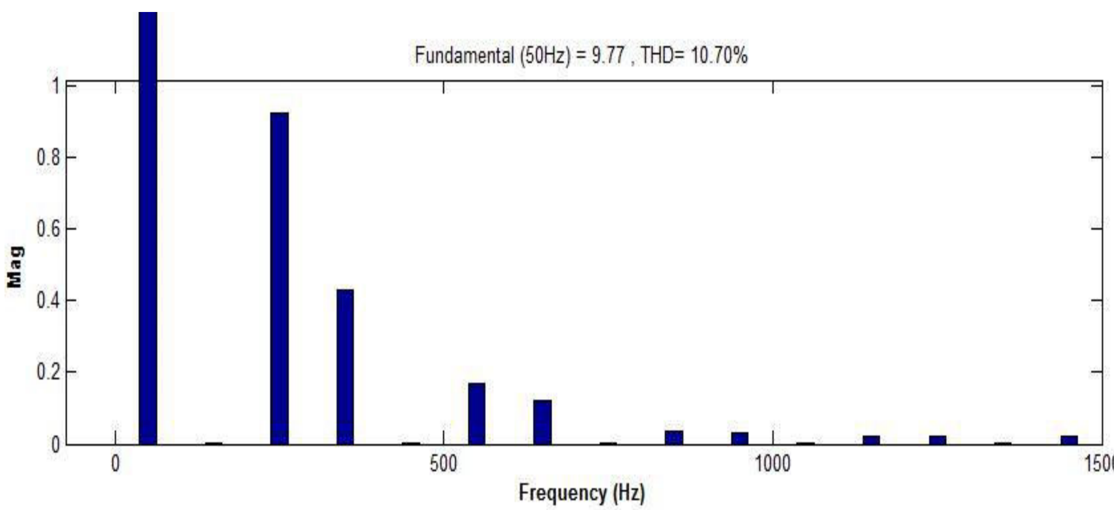

Fig. 5.13 THD of load current

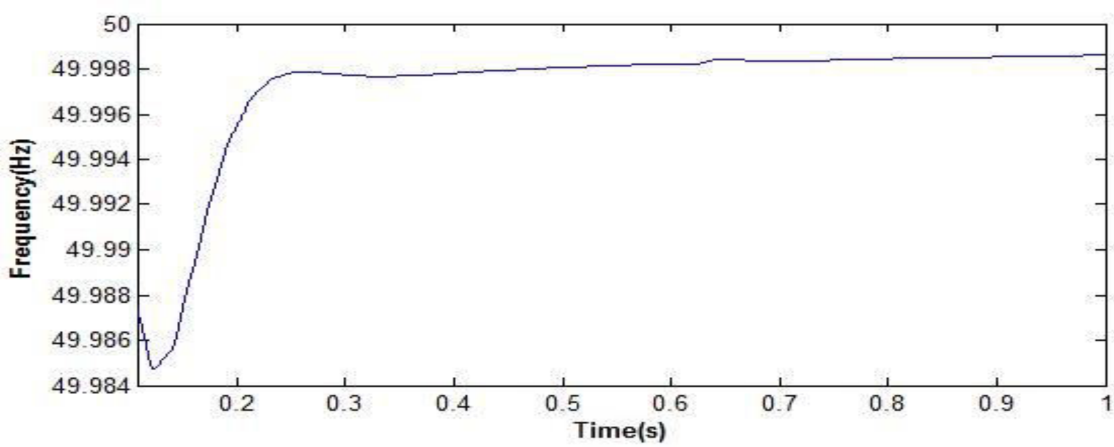

Fig. 5.14 Output frequency of PLL

The controller minimizes the harmonic content of the current up to some extent. The converter control minimizes the grid current harmonics and sends the active power in to the grid. Fig 5.15 and fig 5.16 are the active power and reactive power of grid respectively. As we are controlling the grid to operate in UPF mode hence, the reactive power is zero.

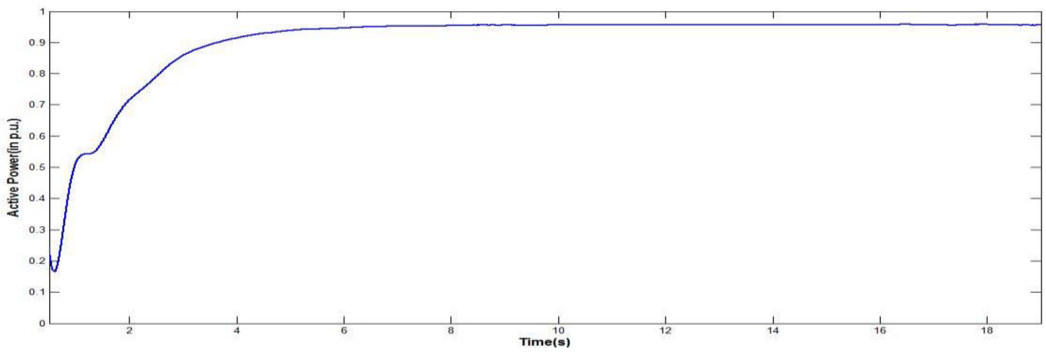

Fig. 5.15 Active Power of utility Grid

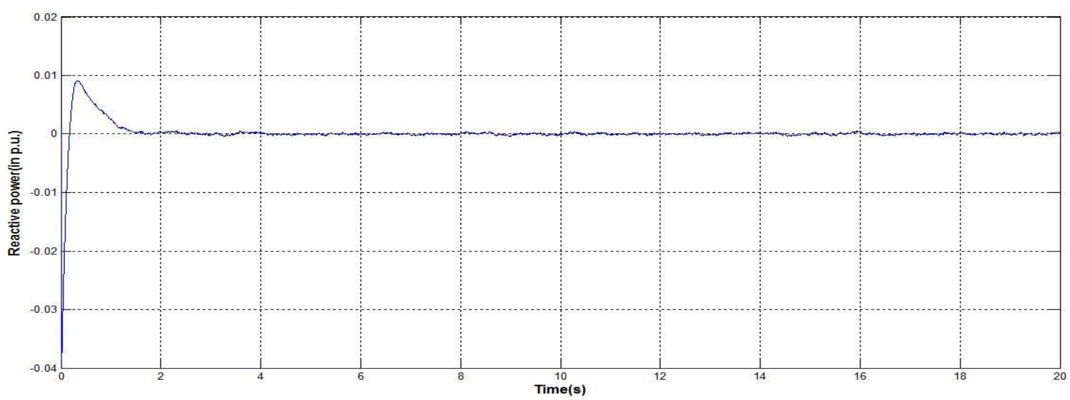

Fig. 5.16 Reactive Power of utility Grid

5.6 Conclusion

This chapter ends with all simulated results of the wind power system connected to utility grid. Using the above controller the grid current harmonics are minimized and it is almost sinusoidal irrespective of the inverter and load current. Here the grid is operated in UPF hence the reactive power obtained is zero.

CHAPTER 6

CONCLUSION AND FUTURE SCOPE

6.1 Conclusion

6.2 Future Scope

6.1 Conclusions

- Wind power system has been studied, and turbine characteristics with the change in wind speed have been simulated. This shows that the turbine power output increases with increase in speed of the wind.

- A maximum power tracking system was designed to coerce peak power for the system using P&O method by changing the duty ratio of the buck-boost converter. We have tracked the maximum power at the maximum voltage and current when the turbine is operated at its optimum speed.

- For grid-connected operation a VS-PWM inverter was implemented with grid synchronization control using voltage oriented vector control approach for UPF operation of the grid. The voltage oriented control is achieved along d-axis.

6.2 Future Scope

- MPP can be tracked using more efficient and more accurate algorithms by which the optimum power can be found more accurately. Another method such as vector control using direct current of the generator can be obtained for the MSC as it has better reliability, stability & efficiency.

- Grid side converter with reactive power compensation and harmonic reduction can be designed. Here the reactive power component is chosen as zero as here we are only controlling the active power for UPF operation.

- A battery charge controller can also be designed for better battery life when the turbine is to be operated in remote places for the stand-alone mode of operation.

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APPENDIX A

A.1: GENERATOR AND TURBINE PARAMETERS

SL NO	PARAMETERS	RATING
01	Base turbine speed(m/s)	10
02	Blade Radius(m)	1
03	Air density(kg/m^3)	1.225
04	Rated Generator Power(VA)	2500
05	Rated Generator Voltage(V)	170
06	Rated frequency	50
07	Stator phase resistance(Ω)	2.875
08	Inductances(L_q,L_d)(mH)	8.5
09	Flux linkage(V.sec)	0.34458
10	Voltage Constant ($V_{peak\ L\text{-}L/krpm}$)	250
10	Pole pair	20

A.2: GRID-SIDE CONVERTER AND GRID SPECIFICATIONS

SL NO	PARAMETERS	RATING
01	Grid base power	1800W
02	Grid Voltage	170V
03	Grid frequency	50Hz
04	DC link capacitor	1.5mF
05	DC link voltage	240V
06	Coupling inductor	1mH