ANALYSIS OF INDUCTION MACHINE
FOR
VARIABLE SPEED WIND POWER GENERATION

A DISSERTATION

Submitted in partial fulfillment of the
requirements for the award of the degree
of
MASTER OF TECHNOLOGY
in
ELECTRICAL ENGINEERING
(With Specialization in Power Apparatus and Electric Drives)

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CANDIDATE'S DECLARATION

I hereby declare that the work which is being presented in the dissertation entitled **'ANALYSIS OF INDUCTION MACHINE FOR VARIABLE SPEED WIND POWER GENERATION'** in partial fulfillment of the requirements for the award of the degree of Master of Technology in Electrical Engineering with specialization in Power Apparatus and Electrical Drives, submitted to the department of Electrical Engineering, Indian Institute of Technology, Roorkee, India is an authentic record of my own work carried out during a period from July 2007 to June 2008 under the guidance and supervision of **Dr. S P Gupta**, Professor, and **Dr. Pramod Agarwal**, Professor, Electrical Engineering department, 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 Institute or any other Institute.

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

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ABSTRACT

Among the renewable sources of energy available today for generation of electrical power, wind energy stands foremost mainly because it is considered to be nonpolluting and economically viable. Design and successful operation of wind energy conversion systems (WECs) is a very complex task involving many interdisciplinary skills, e.g., civil, mechanical, electrical and electronics, geography, aerospace, environmental etc. Performance of WECs depends upon subsystems like wind turbine (aerodynamic), gears (mechanical), generator and converters (electrical); whereas the availability of wind resources are governed by the climatic conditions of the region concerned for which wind survey is extremely important to exploit wind energy.

In this dissertation, grid connected doubly fed Induction Generator (DFIG) for variable speed wind power generation is described. Line voltage Oriented vector control approach is deployed for both stator- and rotor-side converters to provide independent control of active and reactive power and keep the DC-link voltage constant. To extract maximum energy from the wind, a look-up table is prepared from the wind turbine power speed characteristics curve. The complete simulation model is developed in matlab/simulink.

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1. INTRODUCTION

1.1 GENERAL

As a result of increasing environmental concern, the impact of conventional electricity generation on the environment is being minimized and efforts are made to generate electricity from renewable sources. The main advantages of electricity generation from renewable sources are the absence of harmful emissions and the infinite and free availability of the motive power. One way of generating electricity from renewable sources is to use wind turbines that convert the energy contained in flowing air into electricity [1]. Wind turbines have been in use for more than 1,000 years. The earliest wind turbine designs were extremely simple; turbines were allowed to rotate at a rate proportional to the velocity of the wind. They were used to pump water, grind grain, cut lumber, and perform a myriad of other tasks. For these purposes, varying speed seldom impacted the effectiveness of the windmill enough to justify the complications of closely controlling rotational speed. Allowing the machines to run at variable speed was in fact highly advantageous as it greatly increases the total energy that could be extracted from the wind.

With the advancement of aerodynamic designs, wind turbines that can capture several megawatts of power are available. When such wind energy conversion systems (WECSs) are integrated to the grid, they produce a substantial amount of power, which can supplement the base power generated by thermal, nuclear, or hydro power plants. A WECS can vary in size from a few hundred kilowatts to several megawatts. The size of the WECS largely determines the choice of the generator and converter system.

The cage rotor induction machine is the most frequently used generator for grid-connected WECS. When connected to the constant frequency network, the induction generator runs at near-synchronous speed, drawing the magnetizing current from the mains, thereby resulting in constant speed constant frequency (CSCF) operation. However, if there is flexibility in varying the shaft speed, the energy capture due to fluctuating wind velocities can be substantially improved. The requirement for variable-speed constant frequency (VSCF) operation led to several developments in the generator control of WECS. By using back-to-back PWM inverters between the grid and the machine and employing vector control techniques, the active and reactive powers handled by the machine can be controlled independently.

Rotor side control of a grid-connected wound rotor induction machine is very attractive for such VSCF application, particularly when the speed range is limited. With a suitable integrated approach toward design of a WECS, use of a slip-ring induction generator is economically competitive, when compared to a cage rotor induction machine. The stator is directly connected to the three-phase grid and the rotor is supplied by two back-to-back pulse width modulation (PWM) converters. Such an arrangement provides flexibility of operation in sub-synchronous and super-synchronous speeds both in the generating and motoring modes. The rating of the power converters used in the rotor circuit is substantially lower than the machine rating and is decided by the range of operating speed. The higher cost of the machine due to the slip rings is compensated by a reduction in the sizing of the power converters.

Since the stator is directly connected to the grid, the stator flux is constant over the entire operating region. Therefore, the torque can be maintained at its rated value even above the synchronous speed. This results in higher power output above the synchronous speed (i.e., at high wind velocities) when compared to a cage rotor induction generator of the same frame size. Thus, the machine utilization is substantially improved.

Irrespective of the generator used for a variable-speed WECS, the output energy depends on the method of tracking the peak power points on the turbine characteristics due to fluctuating wind conditions. The conventional method is to generate a look up table for a given rotor speed from the wind turbine wind power characteristics.

1.2 WIND ENERGY IN INDIA

As against the estimated 122,000 MW renewable energy based grid connected power generation potential in the country, so far only about 9500 MW installed capacity has been realized, giving vast opportunity for exploitation of renewable energy sources for power generation. The renewable energy based power generation capacity presently constitutes 6% of the total installed capacity in the country for power generation from all sources. The country is aiming to achieve up to 10% of additional installed capacity to be set up till 2012 to come from renewable energy sources [2].

India has been rated as one of the promising countries for wind power development with an estimated gross potential of 45,000 MW and technically realizable potential of about 13,000 MW. The Indian wind energy sector has an installed capacity of 8757.2 MW (as on March 31, 2008). A Worldwide installed capacity of wind power is approximately 94,000 MW. The top five countries in terms of installed capacity are Germany (22.3 GW), the US (16.8 GW), Spain (15.1 GW), India (8.7 GW) and China (6.1 GW) [3].
The leading wind turbine manufacturers in India include suzlon, Enercon, Vestas-RRB, Elecon, Pioneer, Wincon, and Southern Wind Farms.

1.3 LITERATURE REVIEW

In 1991, Mitsutoshi Yamamoto, Osamu Motoyoshi [26], developed a new power control system for a doubly-fed wound rotor induction generator that has applied a control method using a rotating reference frame fixed on the gap flux of the generator and can control active and reactive power independently and stably. The transmitting characteristics of harmonic currents fed to the rotor windings to the stator winding by changing its frequency has been analyzed and verified by experiments.

In 1992, L. Cadirci, M. Ermiq, have discussed steady-state analysis of a wound-rotor induction generator operated at varying shaft speeds in the sub synchronous and super synchronous regions by using a modified equivalent circuit to maximize the total electrical power output. They solved the resulting nonlinear algebraic equations numerically for an optimum control strategy.

In 1994, M.Y. Ugtug, I. Eskandarzadeh, H.Ince [27], developed a double output induction generator (DOIG) driven by a wind turbine by driving a reference frame model of the system including a fully controlled rectifier on the rotor side to obtain the steady state equations in terms of the stator and rotor currents, rotor voltage and the slip. These equations are solved with a model of a wind turbine driving the DOIG by formulating an optimization problem to investigate the conditions of transferring maximum power from the wind turbine to the grid system in either sub-synchronous or super-synchronous modes.

In 1995, Yifan Tang, Longya Xu [28], dealt with flexible active and reactive power control strategy for slip power recovery system comprising of doubly excited induction machine or doubly excited brushless reluctance machine and PWM converters with a dc link. The control strategy is such that for Variable-speed constant-frequency generating systems used in wind power, the optimal torque speed profile of the turbine can be followed and overall reactive power can be controlled while the machine copper losses have been minimized. At the same time, harmonics injected into the power network has also been minimized which makes the system as both a high-efficient power generator and a flexible reactive power compensator.

In 1996, R. Pena, J.C.Clare, G. M. Asher, dealt with the engineering and design of a doubly fed induction generator (DFIG), using back-to-back PWM voltage-source converters in the rotor circuit. They described that a vector-control scheme for the supply-side PWM converter results in independent control of active and reactive power drawn from the supply, while ensuring sinusoidal supply currents. Vector control of the rotor-connected converter provides for wide speed-range operation; the vector scheme is embedded in control loops which enable optimal speed tracking for maximum energy capture from the wind.

In 1998, E. Muljadi, K. Pierce, P. Migliore, have suggested a variable-speed, constant-pitch wind turbine to evaluate the feasibility of constraining its rotor speed and power output without the benefit of active aerodynamic control devices. A strategy was postulated to control rotational speed by specifying the demanded generator torque. By controlling rotor speed in relation to wind speed, the aerodynamic power extracted by the blades from the wind was manipulated and the blades were caused to stall in high winds.

In 1999, Shibashis Bhowmik, Ren′e Sp′ee, Johan H. R. Enslin [29], discussed a brushless doubly fed machine (BDFM) to develop a variable-speed generation (VSG) wind power generator. The VSG controller employs a wind-speed-estimation-based maximum power point tracker and a heuristic-model-based maximum efficiency point tracker to optimize the power output of the system. The strategy is applicable to all doubly fed configurations, including conventional wound-rotor induction machines, Scherbius cascades, BDFM's, and doubly fed reluctance machines.

In 2001, Debiprasad Panda, Eric L. Benedict, Giri Venkataramanan Thomas A. Lipo, dealt with the prospect of using the doubly-fed induction machine (DFIM) drive for renewable energy sources like wind and wave energy. The state-of-the-art technology uses two back-to-back IGBT converters for controlling the machine and line side interface. They proposed a method to replace one of the IGBT converters by a thyristor bridge and a boost/buck-boost dc-to-dc interface. This converter is capable of bidirectional power flow and has the ability for successful commutation of the thyristors for all super-synchronous and sub-synchronous speed ranges.

In 2001, Pena, R.Cardenas, R.Blasco, R.Asher, G.Clare,J [30], proposed a new control scheme of a variable speed grid connected wind energy generation system. The scheme uses a cage induction generator driven by an emulated wind turbine with two back-to-back voltage fed PWM inverters to interface the generator and the grid. The machine currents are controlled using an indirect vector control technique. The generator torque is controlled to drive the machine to the speed for maximum wind turbine aerodynamic efficiency. The supply side converter currents are also controlled using a vector control approach using a reference frame aligned with stator voltage vector.

In 2002, Rajib Datta and V. T. Ranganathan, illustrated the comparison of grid-connected wound rotor induction machine controlled from the rotor side with both fixed speed and variable speed systems using cage rotor induction machine. The comparison is based on major hardware components required, operating region and energy output due to a defined wind function using the characteristics of a practical wind turbine.

In 2003, Datta R, Ranganathan.V.T, proposed a method of tracking the peak power, which is independent of the turbine parameters and air density. The algorithm searches for the peak power by varying the speed in the desired direction. The generator is operated in the speed control mode with the speed reference being dynamically modified in accordance with the magnitude and direction of change of active power. The peak power points in the p-w curve corresponds to $\frac{\partial P}{\partial w}=0$. This fact is made use of in the optimum point search algorithm.

In 2003, Seung-Ho Song; Shin-il Kang; Nyeon-kun Hahm [31], described implementation of simple ac-dc-ac converter and proposed modular control strategy for grid connected wind power generation system. Line side inverter maintains the dc-link voltage constant and the power factor of line side can be adjusted. Input current reference of boost chopper is decided for maximum power point tracking of the turbine with out any information of wind speed or generator rpm. As the proposed control algorithm does not require any speed sensor for wind speed or generator rpm, construction and installation are simple, cheap and reliable.

In 2005, Badrul H. Chowdhury, Srinivas Chellapilla, proposed a new method for Vector control of a doubly fed induction generator drive for variable speed wind power generation. To independently control active and reactive power, the control scheme uses stator flux-oriented control for the rotor side converter bridge control and grid voltage vector control for the grid side converter bridge using hysteresis modulation that tracks the desired values of phase currents by turning on the upper transistor or the lower transistor depending on the comparison of reference value of phase current, actual phase current and a specified hysteresis level.

In 2005, Yazhou Lei, Alan Mullane, Gordon Lightbody [32], Robert Yacamini, developed a simple DFIG wind turbine model in which the power converter consisting of power control, rotor side and grid side converter control and DC link, is simulated as a controlled voltage source, regulating the rotor current to meet the command of real and reactive power production.

In 2008, R. Fadaeinedjad, M. Moallem, G. Moschopoulos, proposed a new detailed model that solves the drawback of many works in the area of wind turbine simulation which are either a very simple mechanical model with a detailed electrical model, or vice versa. The new model is used to fully study the electrical, mechanical, and aerodynamic aspects of a wind turbine with a doubly fed induction generator that takes into account the effects of interactions between electrical and mechanical components.

1.4 ORGANIZATION OF THE REPORT

- ✓ Chapter 2 discusses variable speed operation of wind turbines, types of wind energy conversion systems, basic DFIG schemes, and four quadrant operation of DFIG through rotor side control.
- ✓ Chapter 3 presents wind turbines with their power speed characteristics, Operating principle of the wind-turbine doubly-fed induction generator, modeling of DFIG and its associated equations.
- ✓ Chapter 4 discusses principle of operation of grid connected DFIG under vector control, vector control of grid and rotor side converters will be described in this chapter.
- ✓ Chapter 5 presents the simulation model of the proposed grid connected DFIG for variable speed wind power generation in matlab/simulink.
- ✓ Chapter 6 discusses the simulation results obtained.
- ✓ Chapter 7 gives the conclusions and the scope for further future work.

1.5 SCOPE OF THE WORK

The present work describes grid connected DFIG for variable speed wind power generation. The wound rotor generator shaft is connected to a wind turbine shaft by means of a gearbox. The stator terminals are directly connected to the grid and the rotor terminals are connected to the grid by means of a back-to-back power converter bridge. The induction machine model is based on the stationary reference frame. Two vector-control schemes are designed for the rotor-side and grid-side PWM converters respectively for decoupled control of active and reactive power. Since the objective is to capture the maximum energy available in the wind, the active power reference is always made equal to the available wind turbine power via a look-up table for a given generator rotor speed.

2. VARIABLE SPEED OPERATION

There are many variable-speed architectures. The different combinations of generators, gearboxes, direct drives, and power electronics allow for a wide range of combinations, particularly when combined with the many available control scenarios. The use of variable speed in wind turbines is now centuries old. Only the methods of implementing variable speed in an electric generating environment are new. These changes are due to new materials, new electrical components and manufacturing processes, new computer control tools, and improved understanding of the interaction of these many variables.

2.1 TYPES OF WIND ENERGY CONVERSION SYSTEMS (WECS)

Wind electric conversion systems can be broadly classified as:

1. Constant speed constant frequency (CSCF)
2. Variable speed constant frequency (VSCF)
3. Variable speed variable frequency (VSVF)

2.1.1 Constant Speed Constant Frequency (CSCF) System

In CSCF scheme the generator is directly connected to the mains supply grid. The frequency of the grid determines the rotational speed of the generator and thus of the rotor. The rotor speed is held constant by continuously adjusting the blade pitch and/or generator characteristics. In order to operate the fixed speed systems at low and high wind speeds efficiently, pole changing is generally employed. Smaller number of pole pairs is used at high wind speeds and higher number at lower wind speeds. This allows the generator to operate at a different mechanical speed without affecting its electrical frequency. The advantage is that a cost-effective aerodynamic control like stall control can be used. However, the drawbacks in fixed speed systems are:

- It cannot optimally use the available wind power due to constant speed operation;
- Since there is no inherent reactive power control method in this configuration, it must use capacitor banks instead of drawing the reactive power from the grid;
- Since the generator is made to run at a constant speed in spite of fluctuations in wind speed, it will result in fluctuation of generated voltage as well as output power.

Constant speed constant frequency (CSCF) WECS using cage rotor induction machines (Fig.2.1) are most widely used because of their design simplicity and low cost [4-5].

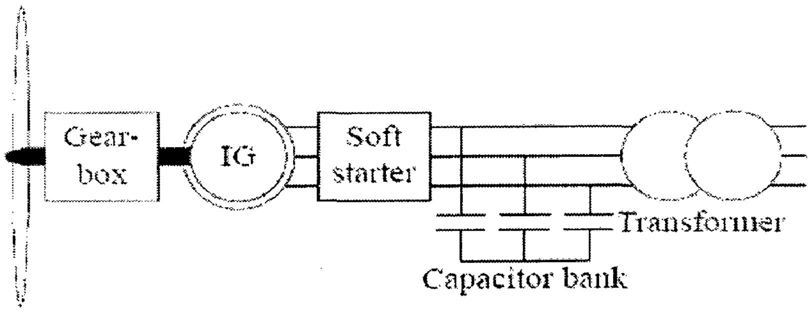

Fig. 2.1 CSCF Using Squirrel Cage Induction Machine Scheme

2.1.2 Variable Speed Constant Frequency (VSCF) System

In variable speed systems, the turbine rotor absorbs the mechanical power fluctuations by changing its speed. So the output power curve is smoother which greatly enhances the quality of power. However, since variable speed operation produces a variable frequency voltage, a power electronic converter must be used to connect to the constant frequency grid. The variable speed operation of a wind energy system is attractive for a number of reasons. It will reduce the mechanical stress in the gear box, increase the amount of energy captures from the wind, which results in higher annual energy yields per rated installed capacity and improve the controllability of the active and reactive power, which becomes more and more important in respect to integrate the wind turbines in to the grid.

2.1.2.1 Variable Speed WECS with Squirrel Cage Induction Generator

In this setup the stator of the squirrel cage induction generator will be connected to the grid by means of back-to-back connected power electronic converter bridges as shown in Fig.2.2.

The converter is needed because the variable speed generator produces a variable frequency voltage that has to be converted to match the constant grid frequency. Since the power converter has to convert all the stator power, the converter size depends on the stator power rating.

The advantages of this configuration are its ability to make the best use of available wind power and the fact that it eliminates the need for a capacitor bank since it is able to draw its required reactive power from the grid. However, the cost of the power converter can be high due to its large size.

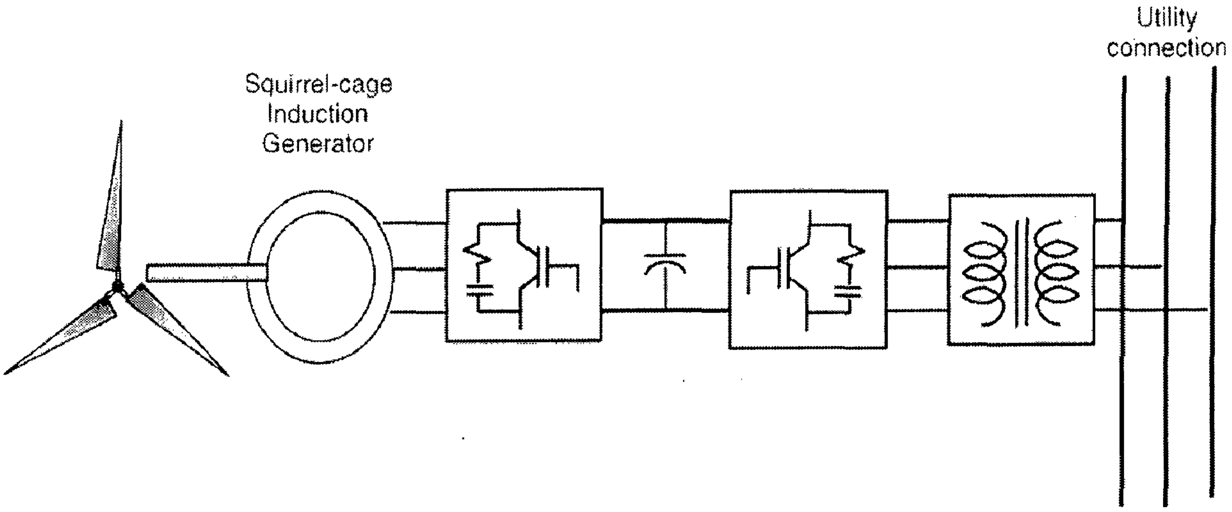

Fig.2.2 Variable Speed WECS with Squirrel Cage Induction Generator

2.1.2.2 Variable Speed WECS with Wound Rotor Induction Generator

Although a squirrel cage induction generator may be used in variable speed WECS, the power converter size in the earlier system can be reduced by using it on the rotor side of a wound rotor induction generator. Fig.2.3 shows a variable speed system using a wound rotor generator. The power converter is now connected between the rotor and grid. So it needs to carry only the slip power, the magnitude of which will be the machine slip times the stator power. In general though, wound rotor induction generators cost more than the squirrel cage type. However, for large ratings, the costs become comparable. So, the net advantages of using a wound rotor generator outweigh that of a squirrel cage machine for utility scale wind power generation

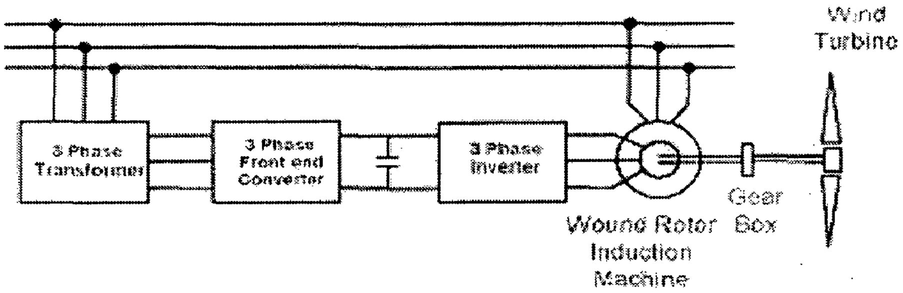

Fig 2.3 Variable Speed WECS with Wound Rotor Induction Generator

2.1.3 Variable Speed Variable Frequency (VSVF) System

The variable speed operation of wind energy conversion systems shows great operation flexibility, resulting in improved use of the available wind energy as well as reduced stress of the electro-mechanical components. This scheme is gaining importance for stand-alone wind power applications. In remote power generation systems, the utilization of variable speed operation applied to water pumping allows an economically attractive solution to the energy storage problem, mainly due to the uncertain nature of primary driving source. Almost in this scheme self excited induction generators (SEIG) are used.

2.2 BASIC DFIG SCHEMES

2.2.1 Static Kramer Drive System

The conventional static Kramer drive consists of a wound rotor induction motor and slip energy recovery circuit comprising a three phase diode bridge rectifier, a DC link smoothing reactor and a three phase line commutated thyristor inverter connected to the AC supply via a recovery transformer needed when stator voltage is higher than rotor voltage [6]. Rotor current, and hence torque and speed, are controlled by varying the inverter firing angle providing one of the simplest and most efficient methods of controlling the speed of an induction motor. It operated only in motoring mode of operation.

The static Kramer drive has been very popular in large power pump and fun type drives, where the range of speed control is limited near, but below synchronous speed. The drive system is very efficient and the converter power rating is low because it has to handle only the slip power. But the drive suffers from a number of drawbacks principally poor power factor, and a highly variable reactive power requirement that is difficult to correct using power factor correction capacitors. The drive is also susceptible to supply dips and failures leading to inverter commutation failure. Other features of drive performance, caused by inclusion of the diode rectifier in the rotor circuit, include torque pulsations at six times slip frequency and low frequency supply current pulsations at certain speed.

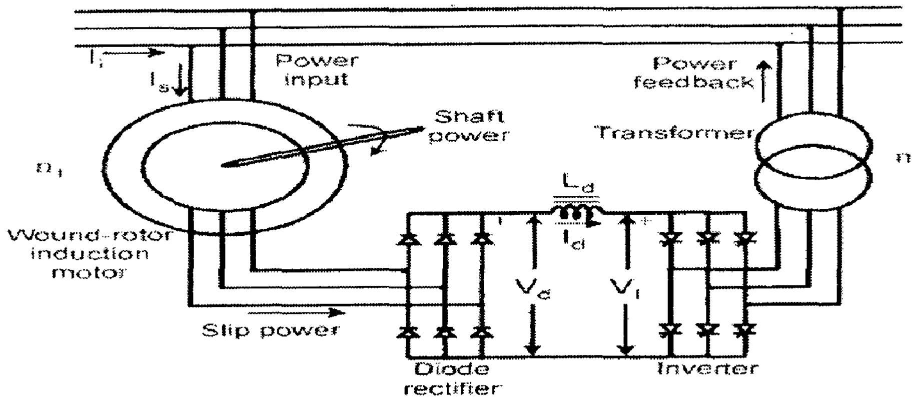

Fig. 2.4 Static Kramer Drive System

2.2.2 Static Scherbius Drive

If the diode rectifier in Fig 2.4 on the machine side is replaced by a thyristor bridge as shown in Fig. 2.5, the slip power can be controlled to flow in either direction. With reverse slip-power flow at sub-synchronous speed, the power corresponding to shaft input mechanical power can be pumped out of the stator. Such a drive system with bidirectional slip power flow can be controlled for motoring and generating in both the sub-synchronous and super-synchronous ranges of speeds.

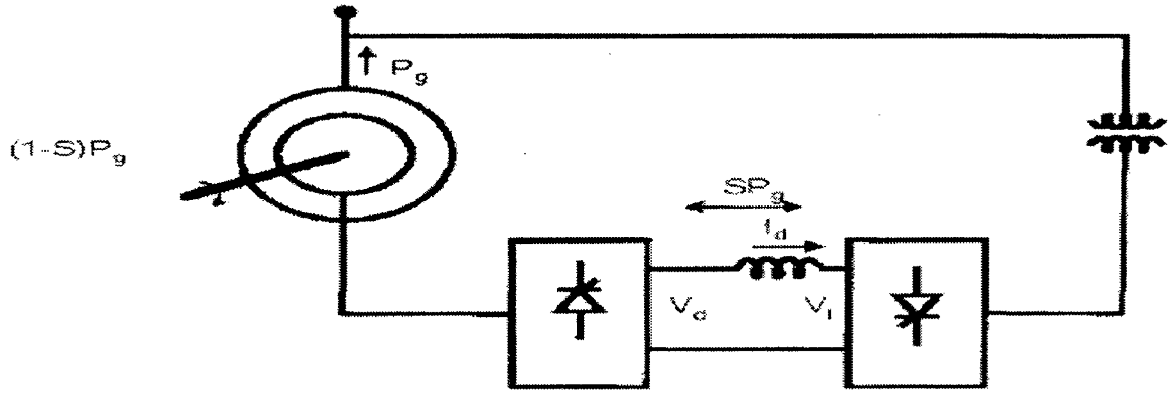

Fig.2.5 Static Scherbius Drive System Using Dc Link Thyristor Converters

The dual-bridge converter system shown above can be replaced by a double-sided, PWM, voltage fed converter system as shown below. The doubly fed induction machine using an AC-AC converter in the rotor circuit (Scherbius drive) has long been a standard drive option for high-power applications involving a limited speed range. The power converter need only be rated to handle the rotor power. Wind-energy generation is regarded as a natural application for the Scherbius DFIG system, since the speed range (from cut-in to rated wind velocity) may be considered restricted.

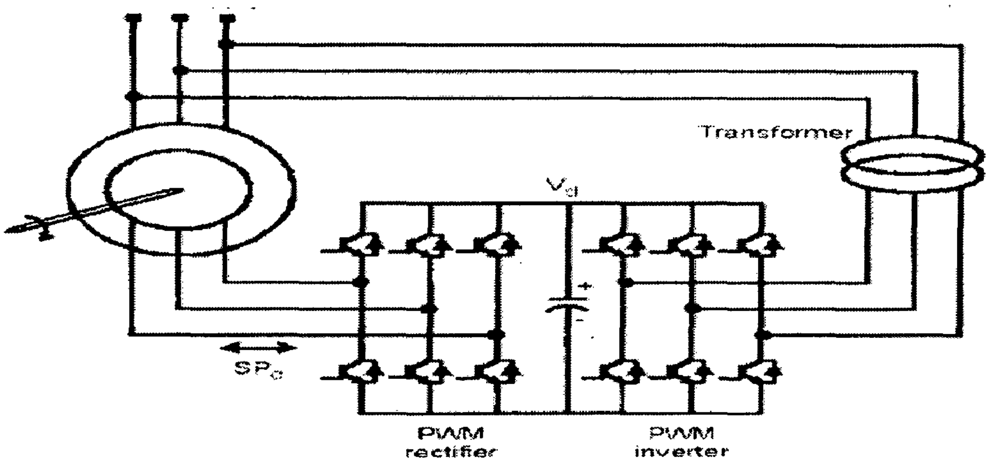

Fig.2.6 Static Scherbius Drive Using Double Sided PWM Voltage-Fed Converter

2.3 FOUR QUADRANT OPERATION OF DFIG THROUGH ROTOR SIDE CONTROL

A doubly-fed induction machine (DFIM) is formed when a power converter is present in the rotor circuit of a wound-rotor induction machine. The DFIM is controlled by directing the power flow into and out of the rotor windings. It has a few distinct advantages over the conventional squirrel cage machine. It can be fed and controlled from either or both the stator and the rotor. Of the different possible combinations, rotor side control is advantageous since the power converter only needs to handle the slip power. Thus, if the machine is operated within a limited slip range, then the power converter rating can be brought down remarkably [7]. Alternatively, if the DFIM is operated at double the rated speed, then the power extracted from the machine is doubled.

The operating region of the system in the torque-speed plane is shown in Fig.2.7. Since the rotor side control strategy becomes advantageous within a limited slip range, the operating region is spread out on both sides of the synchronous speed w_s, implying both sub-synchronous and super-synchronous modes of motoring and generating operations [8-9].

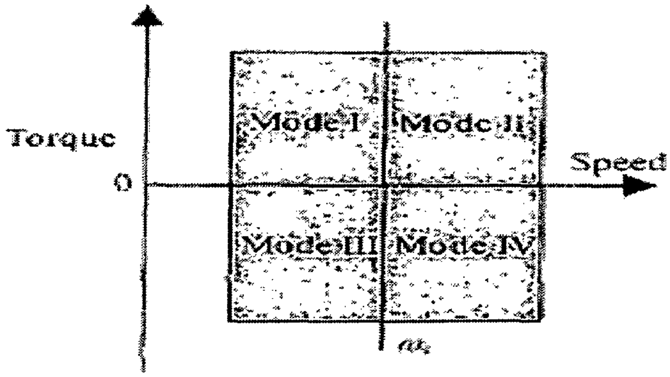

Fig. 2.7 Operating Region with Rotor Side Control

Where:
Mode I is sub-synchronous motoring
Mode II is super-synchronous motoring
Mode III is sub-synchronous generating
Mode IV is super-synchronous generating

The principle of a DFIM control in these modes can be understood by the power flow diagrams given in Figures 2.8a to 2.8d. In these figures, P_s is the stator power, P_r is the rotor power and P_m is the mechanical power [10-11]. When the DFIM is operating as a motor in the sub-synchronous speed range (Figure 2.8a) power is taken out of the rotor. This operational mode is commonly known as slip-power recovery.

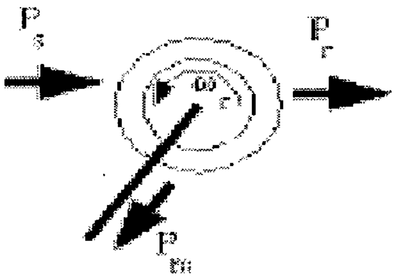

Fig. 2.8a Sub-Synchronous Motoring Operation

If the speed increases so that the machine is operating at super-synchronous speeds (Figure 2.8b) then the rotor power changes direction from the sub-synchronous operation.

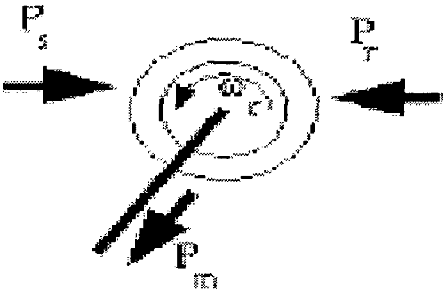

Fig.2.8b Super-Synchronous Motoring Operation

When the DFIM is operating as a generator in the sub synchronous speed range (Figure 2.8c) power is delivered to the rotor.

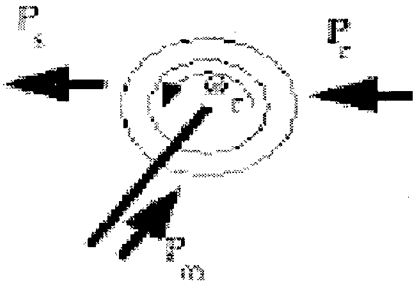

Fig. 2.8c Sub-Synchronous Generating Operation

If the speed increases so that the machine is operating at super-synchronous speeds (Figure 2.8d) then the rotor power changes direction from the sub-synchronous operation.

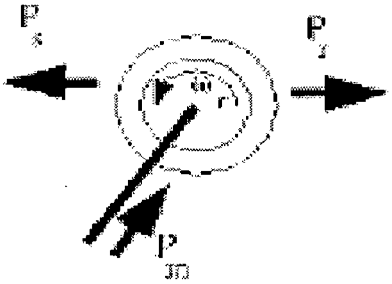

Fig. 2.8d Super-Synchronous Generating Operation

3. DFIG DRIVEN BY A WIND TURBINE

3.1 WIND TURBINE

A wind turbine is a machine for converting the kinetic energy in wind into mechanical energy. The working principle of a wind turbine encompasses two main conversion processes. The turbine consists of a rotor that extracts kinetic energy from the wind and converts it into a rotating movement. This is then converted into electricity by a generator.

The major components of modern wind energy systems typically consist of the following:

- Rotor, with 2 or 3 blades, which converts the energy in the wind into mechanical energy onto the rotor shaft;
- Gearbox to match the slowly turning rotor shaft to the electric generator;
- Tall tower which supports the rotor high above the ground to capture the higher wind speeds;
- Solid foundation to prevent the wind turbine from blowing over in high winds and/or icing conditions and
- Control system to start and stop the wind turbine and to monitor proper operation of the machinery.

3.1.1 Types of Wind Turbines

Wind turbines can be separated into two types; horizontal and vertical based on the axis about which the turbine rotates. They can also be classified by the location in which they are to be used as Onshore, offshore or even aerial wind turbines [12-13].

3.1.1.1 Horizontal Axis Wind Turbines (HAWT)

In HAWT, the axis of rotation is parallel to the direction of the wind. These types of turbines have the main rotor shaft and electrical generator at the top of a tower, and must be pointed into the wind. Small turbines are pointed by a simple wind vane, while large turbines generally use a wind sensor coupled with a servo motor. Depending upon the orientation of the blades with respect to wind direction these may be classified as up-wind and down-wind type. Most have a gearbox, which turns the slow rotation of the blades into a quicker rotation that is more suitable for generating electricity.

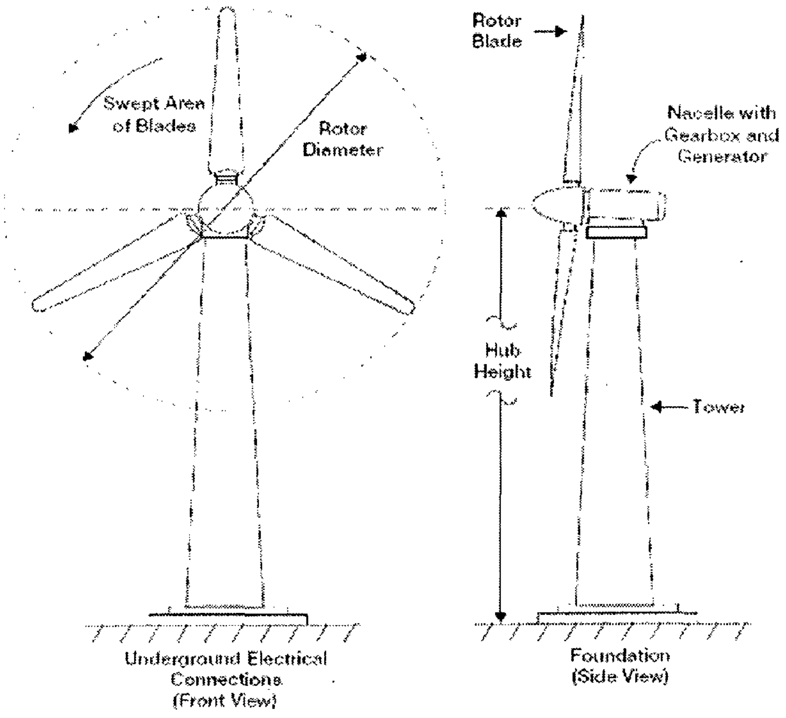

Fig. 3.1 Wind Energy System Schematic (HAWT)

3.1.1.2 Vertical Axis Wind Turbines (VAWT)

In VAWT, the axis of rotation is perpendicular to the direction of wind. These machines are also called as cross-wind axis machines. The principal advantages of VAWT over conventional HAWT are that VAWT are omni directional, i.e. they accept the wind from any direction. The vertical axis rotation permits mounting the generator and gear at the ground level. On the negative side VAWT requires guy wires attached to the top for the support, which may limit its application particularly for the offshore sites. Drawbacks are usually the pulsating torque that can be produced during each revolution and the drag created when the blade rotates into the wind. It is also difficult to mount vertical-axis turbines on towers, meaning they must operate in the often slower, more turbulent air flow near the ground, with resulting lower energy extraction efficiency. Vertical-axis turbines are less frequently used.

3.2 POWER IN THE WIND

Wind turbines convert the kinetic energy present in the wind into mechanical energy by means of producing torque and it is characterized by its power-speed characteristics. Since the energy contained by the wind is in the form of kinetic energy, its magnitude depends on the air density and the wind velocity.

For a horizontal axis wind turbine, the amount of power P_m that a turbine is capable of producing is given by

$$P_m = \frac{1}{2} C_p \rho A V^3 \qquad (3.1)$$

where P_m is the turbine mechanical power, ρ is the density of the air in kg/m3, A is the exposed area in m^2, and V is the velocity in m/s.

C_p is called the power coefficient and gives the fraction of the kinetic energy that is converted into mechanical energy by the wind turbine. It is a function of the tip speed ratio λ and depends on the blade pitch angle for pitch-controlled turbines. The tip speed ratio may be defined as the ratio of turbine blade linear speed and the wind speed:

$$\lambda = \frac{W_t R}{V} \qquad (3.2)$$

Where R is the radius of the turbine and

w_t is the turbine rotational speed

A typical relationship between C_p and λ (for maximum pitch angle) is shown in fig. 3.2 [14]. It is clear from this figure that there is a value of λ for which C_p is maximized thus maximizing the power for a given wind speed.

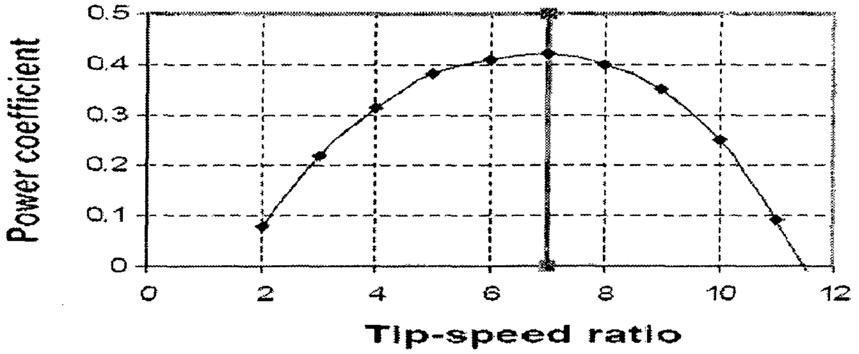

Fig 3.2 C_p *vs* λ Characteristics for 0 Pitch Angle

Because of the relationship between C_p and λ, as the turbine speed changes for a given wind velocity there is a turbine speed that gives a maximum output power. This is shown in fig. 3.3 for various wind speeds [15]. As seen in the figure the peak power for each wind speed occurs at the point where C_p is maximized. The prime motivation for variable speed control of WECS is to track the rotor speed with changing wind velocity so that is always maintained at its maximum C_p value. To maximize the power generated it is therefore desirable for the generator to have a power characteristic that will follow the maximum C_p line.

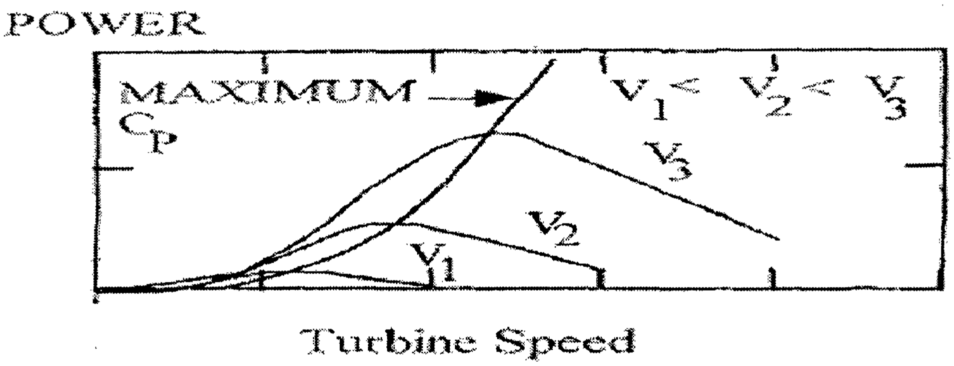

Fig.3.3 Typical Turbine Power Relationship for Various Wind Speeds

There is a range of methods for controlling aerodynamic forces on the turbine rotor and therefore limiting the peak power output of a turbine. The simplest is passive stall control [16] in which the design of rotor aerodynamics causes the rotor to stall (loose power) when the wind velocities exceed a certain value. Other methods include yawing, in which the rotor is turned out of alignment with the wind, by some mechanical device, when a given wind speed is exceeded. The most sophisticated method is active aerodynamic control, such as flaps or full span pitch control. The latter can be implemented as an emergency control method that only feathers the blades in an over speed condition. Alternatively, it can be a highly active method for starting the rotor and controlling power output over a wide range of wind speeds [17].

3.3 PITCH CONTROL

The aerodynamic model of the wind turbine has shown that the aerodynamic efficiency is strongly influenced by variation of the blade pitch with respect to the direction of the wind or to the plane of rotation. Small changes in pitch angle can have a dramatic effect on the power output.

In low to moderate wind speeds, the turbine should simply try to produce as much power as possible, so there is generally no need to vary the pitch angle. The pitch angle should only be at its optimum value to produce maximum power. In high wind speeds, pitch control provides a very effective means of regulating the aerodynamic power and loads produced by the rotor so that design limits are not exceeded.

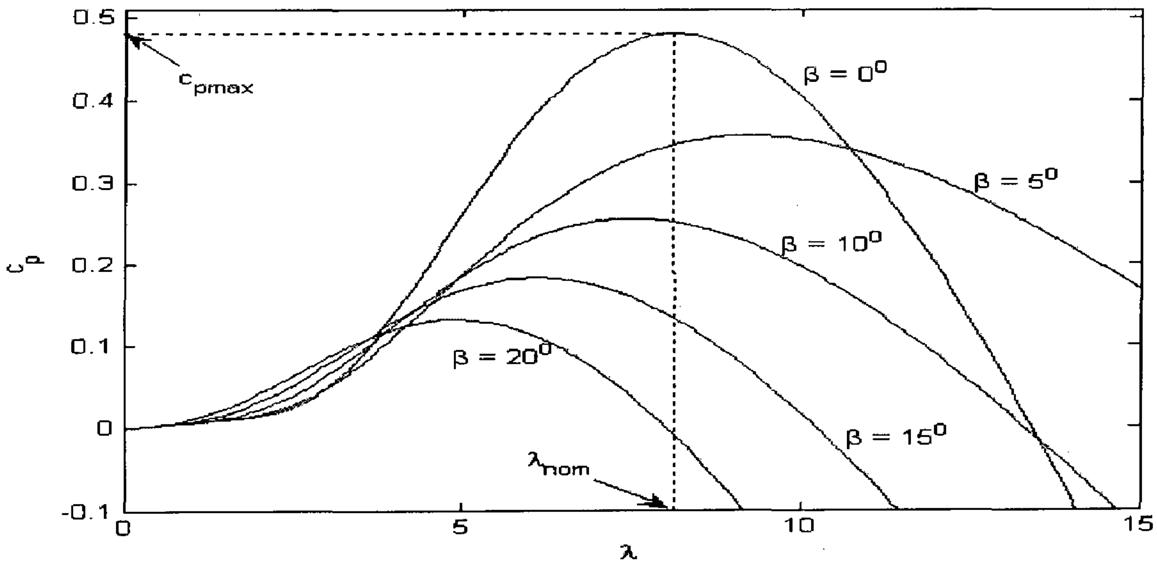

Fig.3.4 C_p vs λ Characteristics for Different Value of Pitch Angle

3.4 OPERATING PRINCIPLE OF WIND-TURBINE DOUBLY-FED INDUCTION GENERATOR

The wind turbine and the doubly-fed induction generator are shown in Fig. 3.5. The AC/DC/AC converter is divided into two components: the rotor-side converter (C_{rotor}) and the grid-side converter (C_{grid}). C_{rotor} and C_{grid} are Voltage-Sourced Converters that use forced-commutated power electronic devices (IGBTs) to synthesize an AC voltage from a DC voltage source. A capacitor connected on the DC side acts as the DC voltage source [18]. A coupling choke (resistor and inductor) is used to connect the grid side converter to the grid. The three-phase rotor winding is connected to C_{rotor} by slip rings and brushes and the three-phase stator winding is directly connected to the grid. The power captured by the wind turbine is converted into electrical power by the induction generator and it is transmitted to the grid by the stator and the rotor windings. The control system generates the pitch angle command and the voltage command signals V_r and V_{gc} for C_{rotor} and C_{grid} respectively in order to control the power of the wind turbine, the DC bus voltage and the voltage at the grid terminals.

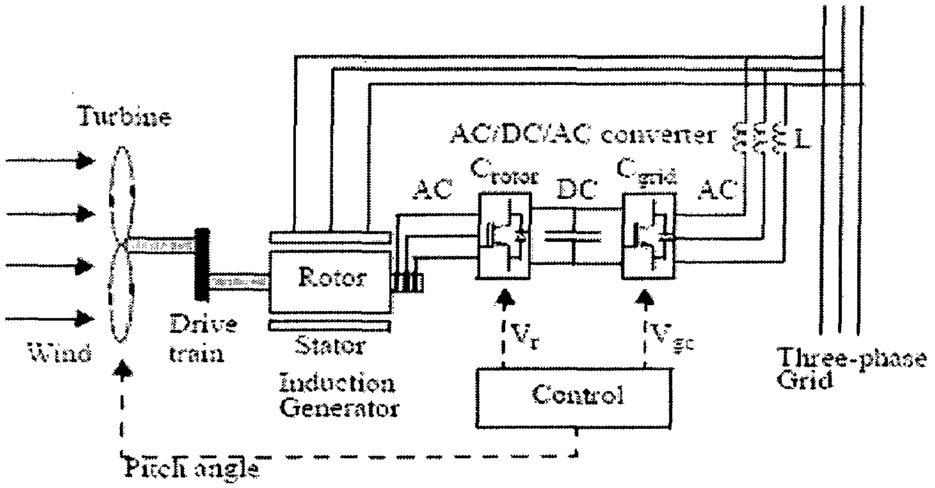

Fig.3.5 Wind Turbine and the Double Fed Induction Generator System

The power flow, illustrated in Fig. 3.6, is used to describe the operating principle. Parameters used in this figure are described in appendix A.

The mechanical power and the stator electrical power output are computed as follows:

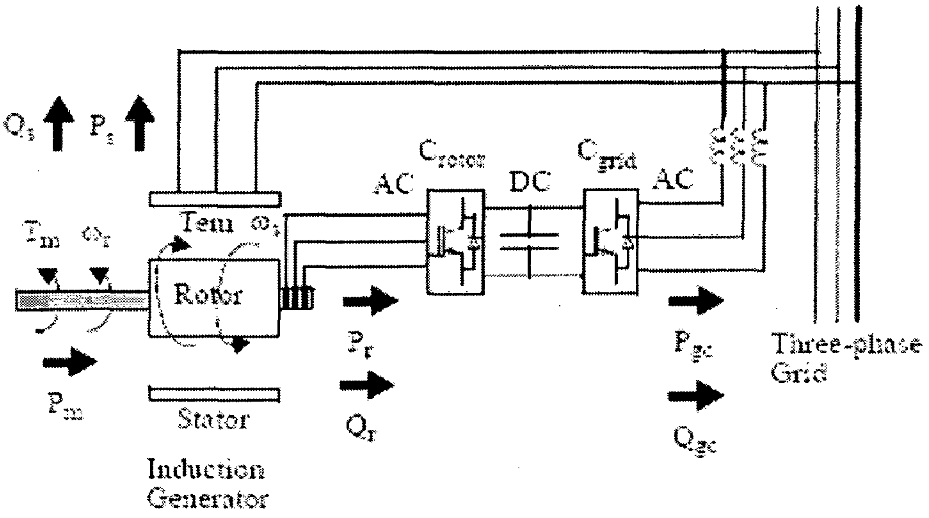

Fig 3.6 Active and reactive power flows

$$P_m = T_m w_r$$
$$P_s = T_{em} w_s \qquad (3.3)$$

For a lossless generator the mechanical equation is:

$$\frac{J \partial w_r}{\partial t} = T_m - T_{em} \qquad (3.4)$$

In steady-state at fixed speed for a lossless generator

$$T_m = T_{em}$$
$$and \ P_m = P_s + P_r \qquad (3.5)$$

It follows that:

$$P_r = P_m - P_s = T_m w_r - T_{em} \ w_s = - sP_s \qquad (3.6)$$

Where

$s = \frac{(w_s - w_r)}{w_s}$, is defined as the slip of the induction generator

Generally the absolute value of slip is much lower than 1 and, consequently, P_r is only a fraction of P_s. For super synchronous speed operation, P_r is transmitted to DC bus capacitor and tends to rise the DC voltage. For sub-synchronous speed operation, P_r is taken out of DC bus capacitor and tends to decrease the DC voltage.

3.5 DFIG MODELING IN D-Q REFERENCE FRAME

The general model for wound rotor induction machine is similar to any fixed-speed induction generator as follows [19]. The parameters used are specified in appendix A.

Voltage Equations:

Stator Voltage Equations:

$$
\begin{aligned}
V_{qs} &= P\lambda_{qs} + w_s\lambda_{ds} + r_s i_{qs} \\
V_{ds} &= P\lambda_{ds} - w_s\lambda_{qs} + r_s i_{ds}
\end{aligned}
\tag{3.1}
$$

Rotor Voltage Equations:

$$
\begin{aligned}
V_{qr} &= P\lambda_{qr} + (w_s - w_r)\lambda_{dr} + r_r i_{qr} \\
V_{dr} &= P\lambda_{dr} - (w_s - w_r)\lambda_{qr} + r_r i_{dr}
\end{aligned}
\tag{3.2}
$$

Power Equations:

$$
\begin{aligned}
P_s &= \frac{3}{2}(V_{ds} i_{ds} + V_{qs} i_{qs}) \\
Q_s &= \frac{3}{2}(V_{qs} i_{ds} - V_{ds} i_{qs})
\end{aligned}
\tag{3.3}
$$

3.3. Torque Equation:

$$
T_{em} = \frac{-3}{2}\frac{p}{2}(\lambda_{ds} i_{qs} - \lambda_{qs} i_{ds})
\tag{3.4}
$$

Flux Linkage Equations:

Stator Flux Equations:

$$
\begin{aligned}
\lambda_{qs} &= (L_{1s} + L_m) i_{qs} + L_m i_{qr} \\
\lambda_{ds} &= (L_{1s} + L_m) i_{ds} + L_m i_{dr} \\
\lambda_s &= \sqrt{(\lambda^2{}_{ds} + \lambda^2{}_{qs})}
\end{aligned}
\tag{3.5}
$$

The air-gap flux linkage Equations:

$$
\begin{aligned}
\lambda_{mq} &= L_m (i_{qs} + i_{qr}) \\
\lambda_{md} &= L_m (i_{ds} + i_{dr}) \\
\lambda_m &= \sqrt{(\lambda^2{}_{dm} + \lambda^2{}_{qm})}
\end{aligned}
\tag{3.6}
$$

Rotor Flux Equations:

$$
\begin{aligned}
\lambda_{qr} &= (L_{1r} + L_m) i_{qr} + L_m i_{qs} \\
\lambda_{dr} &= (L_{1r} + L_m) i_{dr} + L_m i_{ds} \\
\lambda_r &= \sqrt{(\lambda^2{}_{dr} + \lambda^2{}_{qr})}
\end{aligned}
\tag{3.7}
$$

Equivalent circuit representation of an induction machine in arbitrary reference frame is shown below [20].

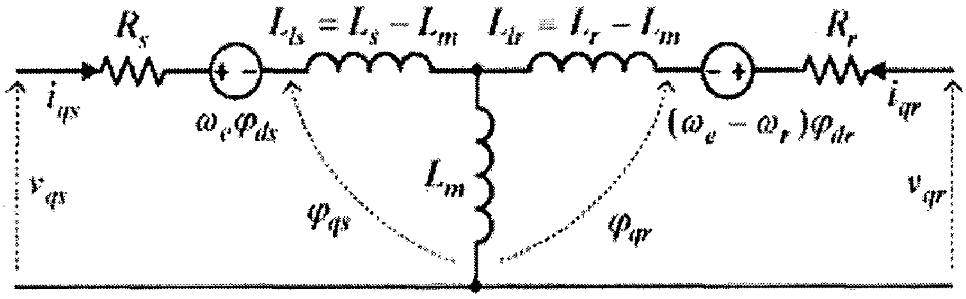

Fig.3.7a q-axis Equivalent Circuit

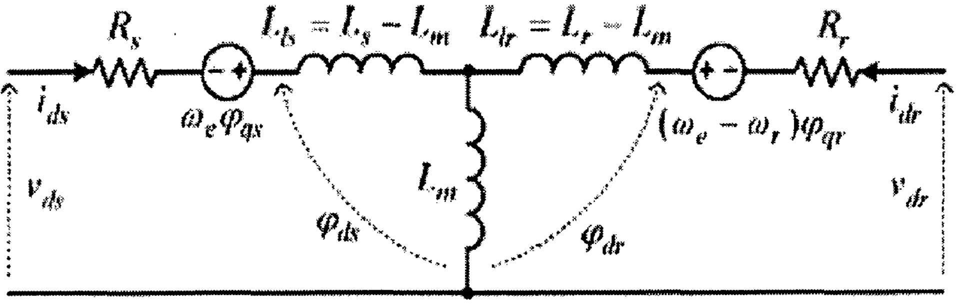

Fig. 3.7b d-axis Equivalent Circuit

4. VECTOR CONTROL OF DFIG

4.1 INTRODUCTION

Double-fed induction machines can be operated as a generator as well as a motor in both sub-synchronous and super synchronous speeds, thus giving four possible operating modes. Only the two generating modes at sub-synchronous and super synchronous speeds are of interest for wind power generation. Thus, two power converter bridges connected back-to-back by means of a dc link can accommodate the bidirectional rotor power flow in a DFIG.

Variable speed operation of the wind turbine can be realized by appropriate adjustment of the rotor speed and pitch angle. For a variable speed wind turbine with a doubly fed induction machine, it is possible to control the load torque at the generator directly, so that the speed of the turbine rotor can be varied within certain limits. An advantage of the variable speed wind turbine is that the rotor speed can be adjusted in proportion to the wind speed in low to moderate wind speeds so that the optimal tip speed ratio is maintained. At this tip speed ratio the aerodynamic efficiency, C_p, is at maximum, which means that the energy conversion is maximized.

In general, variable speed wind turbines may have two different control goals, depending on the wind speed. In low to moderate wind speeds, the control goal is maintaining a constant optimum tip speed ratio for maximum aerodynamic efficiency.

In high wind speeds, the control goal is to keep the rated output power fixed in order not to overload the system.

Two control schemes are implemented in the wind turbine model: speed control and pitch control. The speed control can be realized by adjusting the generator power or torque. The pitch control is a common control method to regulate the aerodynamic power from the turbine.

4.2 PRINCIPLES OF OPERATION

Fig.4.1 shows the basic scheme adopted in the majority of systems [21]. The stator is directly connected to the AC mains, while the wound rotor is fed from the Power Electronics Converter via slip rings to allow DFIG to operate at a variety of speeds in response to changing wind speed. Indeed, the basic concept is to interpose a frequency converter between the variable frequency induction generator and fixed frequency grid. The DC capacitor linking stator- and rotor-side converters allows the storage of power from induction generator for further generation.

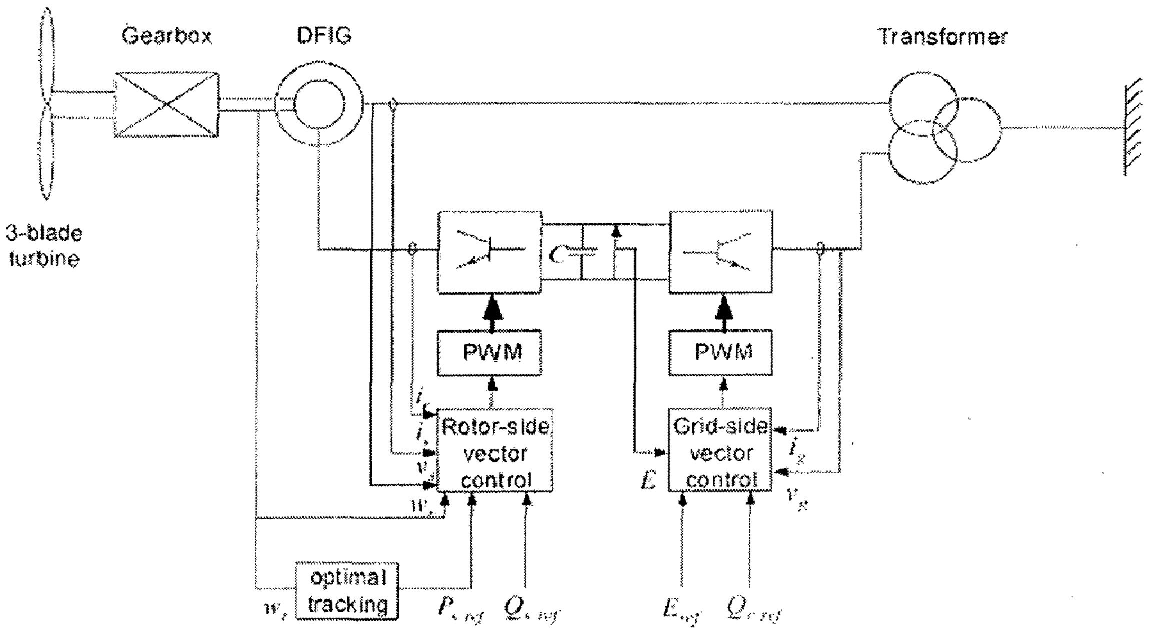

Fig.4. 1 Vector Control Scheme for Double Fed Induction Generator

Two voltage-fed PWM converters are inserted in the rotor circuit, with the supply-side PWM converter connected to the stator/supply via three single- phase chokes. The voltage-transfer characteristics of the system, including the three phase back-to-back PWM converters, are given approximately by [22]:

$$\begin{aligned}
V_s &= m_1 \frac{\sqrt{3}E}{2\sqrt{2}} \\
V_r &= \pm s \frac{V_s}{n} = m_2 \frac{E}{2\sqrt{2}} \qquad (4.1) \\
s &= \pm \frac{n m_2}{\sqrt{3} m_1}
\end{aligned}$$

Where n is the stator-rotor turns ratio of the DFIG, s is the slip and m_1, m_2 are the PWM modulation depths of the stator-side and rotor side converters respectively. Equation 4.1 determines the speed range of the generator. For wind generation, a restricted speed range is acceptable on account of a minimum wind velocity (the cut-in speed), below which very little energy is extractable. The generator speed corresponding to rated wind velocity can be set at any point by the choice of gearbox ratio. Of course, to get the maximum benefit from the Scherbius scheme, this point should be well above synchronous speed where power is extracted from both the rotor and stator of the machine. Eventually, however, as the slip is increased, the system efficiency starts to decrease since more power passes through the DC link converters and the rotor iron and frictional losses increase.

Two vector-control schemes are designed respectively for the rotor-side and grid-side PWM converters, as shown in Fig 4.1. The parameters are specified in appendix A. Below the synchronous speed in the motoring mode and above the synchronous speed in the generating mode, rotor-side converter operates as a rectifier and stator-side converter as an inverter, where slip power is returned to the stator. Below the synchronous speed in the generating mode and above the synchronous speed in the motoring mode, rotor-side converter operates as an inverter and stator-side converter as a rectifier, where slip power is supplied to the rotor. At the synchronous speed, slip power is taken from supply to excite the rotor windings and in this case machine behaves as a synchronous machine.

4.3 CONTROL OF GENERATOR AND ITS ASSOCIATED CONVERTERS

The main control objective considered is the regulation of DFIM stator-side active and reactive powers (i.e. the active and reactive power exchanged between the line grid and the stator port of the DFIM). The stator active power control objective is significant for energy generation applications since, given a prime mover able to produce a given power at a given speed, it is possible to compute the stator power which must be imposed to have a total DFIM active power equal to that available from the prime mover (keeping in mind the overall efficiency) at the considered speed. Alternatively, the control of stator reactive power is relevant since it can coincide with the control of the total reactive power delivered by the DFIM system if a vector-controlled rectifier is adopted at rotor side imposing the exchange of active power only with the line grid. When the power losses in the converters are neglected, the total real power injected into the main network equals to the sum of the stator power and the rotor power. The reactive power exchanged with the grid equals to the sum of stator reactive power and that of grid side converter.

4.3.1 Grid (Supply) Side Converter Control

The objective of the vector-control scheme for the grid-side PWM converter is to keep the DC-link voltage constant regardless of the magnitude and direction of the rotor power, while keeping sinusoidal grid currents. The synchronous reference frame can be linked to the stator or rotor flux of the machine. However, a reference frame linked to the supply (grid) voltage space vector V_s is a convenient alternative because the DFIG operates as a generator maintaining or being fed with constant supply voltage.

Decoupled control of active and reactive powers flowing between rotor and grid is done by using supply voltage vector oriented control ($d^e - q^e$). All voltage and current quantities are transformed to a special reference frame that rotates at the same speed as the supply voltage space phasor with the real axis (d-axis) of the reference frame aligned to the supply voltage vector. At steady state, the reference frame speed equals the synchronous speed. In such a scheme, current $i^e{}_{gd}$ is controlled to keep the dc link voltage constant and current $i^e{}_{gq}$ is used to obtain the desired value of reactive power flow between the supply side converter and the supply. It may also be responsible for controlling reactive power flow between the grid and the grid side converter by adjusting $Q_{r,ref}$.

The scheme makes use of the supply voltage angle determined dynamically to map the supply voltage, the converter terminal voltage and the phase currents onto the new reference frame. First the supply voltage angle (θ) has to be determined.

By definition, the supply voltage angle is [23]:

$$\theta = \tan^{-1}\left(\frac{V_{sq}}{V_{sd}}\right) \tag{4.2}$$

The supply voltage angle is used to map the grid side converter current onto the new reference frame.

$$\begin{bmatrix} i^e{}_{gq} \\ i^e{}_{gd} \\ i^e{}_0 \end{bmatrix} = k_s(\theta) \begin{bmatrix} i_{gq} \\ i_{gd} \\ i_0 \end{bmatrix} \tag{4.3}$$

$$k_s(\theta) = \frac{2}{3} \begin{bmatrix} \cos(\theta) & \cos(\theta - 2\pi/3) & \cos(\theta + 2\pi/3) \\ \sin(\theta) & \sin(\theta - 2\pi/3) & \sin(\theta + 2\pi/3) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \tag{4.4}$$

Equation 4.4 is the Park's transformation matrix

The space location of DFIM vectors in the line-voltage-vector-oriented reference frame is shown in Fig. 4.2. Here ρ_s is taken as θ, x-y is the new reference frame $(d^e - q^e)$.

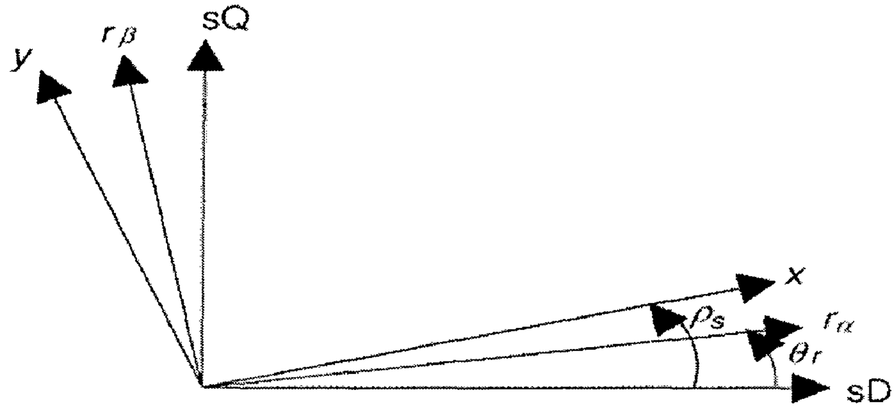

Fig. 4.2 Reference Frames

Aligning the d-axis of the reference frame along the supply-voltage position, $V^e{}_{sq} = 0$, and, since the amplitude of the supply voltage is constant $V^e{}_{sd}$ is constant. The active and reactive power will be proportional to $i^e{}_{gd}$ and $i^e{}_{gq}$ respectively. The PWM converter is current regulated, with the direct axis current used to regulate the DC-link voltage and the quadrature axis current component used to regulate the reactive power.

$$\begin{aligned} P_{gc} &= \frac{3}{2}\left(V^e{}_{sd} i^e{}_{gd} + V^e{}_{sq} i^e{}_{gq}\right) = \frac{3}{2}(V^e{}_{sd} i^e{}_{gd}) \\ Q_{gc} &= \frac{3}{2}(V^e{}_{sq} i^e{}_{gd} - V^e{}_{sd} i^e{}_{gq}) = -\frac{3}{2}(V^e{}_{sd} i^e{}_{gq}) \end{aligned} \tag{4.5}$$

The dc power has to be equal to the active power flowing between the grid and the grid side converter. Thus,

$$\begin{aligned} Ei_{os} &= \frac{3}{2}(V^e{}_{sd} i^e{}_{gd}) \\ C\frac{\partial E}{\partial t} &= i_{os} - i_{or} \end{aligned} \tag{4.6}$$

Where, i_{os} is the current between the dc link and the stator and i_{or} is the current between the dc link and the rotor. Thus, the dc link voltage can be controlled by controlling i^e_{gd} .

The grid side converter control begins with transforming the supply voltages to the stationary reference frame to obtain the voltage vector angle as given by Eq. (4.2). As seen before, the dc link voltage can be controlled by control of the direct axis current i^e_{gd} in the voltage vector-oriented reference frame. The control scheme thus utilizes current control loops for i^e_{gd} and i^e_{gq} with the i^e_{gd} demand being derived from the DC-link voltage error through a standard PI controller as shown in Fig.4.3. The current i^e_{gq} reference was forced to zero so as to make the displacement equal to zero.

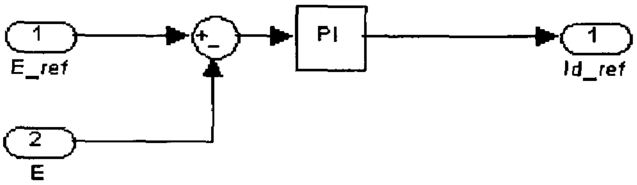

Fig.4.3 Reference Current from Dc Link Voltage Error

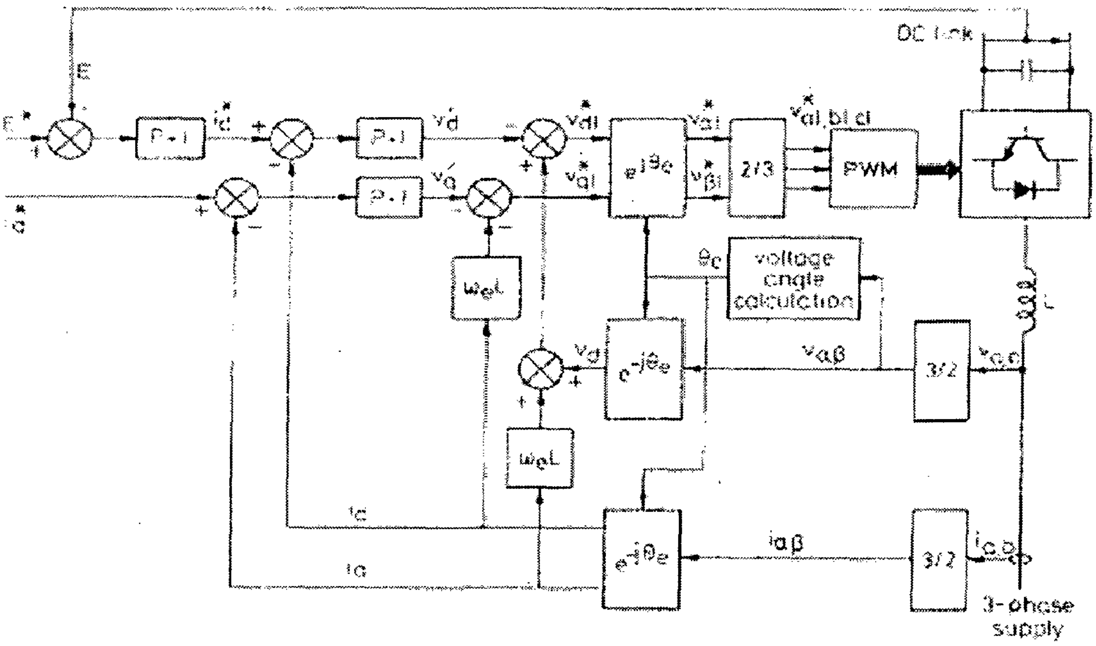

Fig.4.4 Vector Control Scheme for Supply Side Converter from [22]

To obtain exact decoupling some compensation terms are added to the reference voltages as follows:

$$\begin{aligned} V_{sd,ref} &= -V_{sd,ref} + (w_e L i_q + V_{sd}) \\ V_{sq,ref} &= -V_{sq,ref} - (w_e L i_d) \end{aligned} \qquad (4.7)$$

In eqn. above, $V_{sd,ref}$ and $V_{sq,ref}$ are the reference values for the supply-side converter, and the terms in brackets constitute voltage-compensation terms to get a good tracking.

4.3.2 Rotor-Side Converter Control

The vector-control scheme for the rotor-side PWM converter ensures decoupling control of stator-side active and reactive power drawn from the grid. To exploit the advantages of variable speed operation, the tracking of optimum torque-speed curve is essential. Speed can be adjusted to the desired value by controlling torque. So, an approach of using active power set point from the instantaneous value of rotor speed and controlling the rotor current i^e_{rd} in line voltage reference frame to get the desired active power will result in obtaining the desired values of speed and torque according to the optimum torque speed curve. The reactive power set point can also be calculated from active power set point using a desired power factor. The reference value of the stator-side active power is obtained via a look-up table for a given generator rotor speed, which enables the optimal power tracking for maximum energy capture from the wind. It also provides the generator with wide speed-range operation. Normally, the reference values of both stator-side and rotor side reactive power, $Q_{s,ref}$ $Q_{r,ref}$ and are all set to zero to ensure unity power factor operation of the studied wind turbine.

In line voltage oriented control, both measured quantities, i.e. stator and rotor current i_s and i_r are transformed into a special reference frame that rotates at an angular frequency identical to the line (stator) voltage space phasor with the real axis (d-axis) of the reference frame aligned to the line voltage vector. At steady state, the reference frame speed equals the synchronous speed. A decoupling circuit calculates from the desired active and reactive power signals the rotor voltage command V_{dr} and V_{qr}. A reverse vector rotation computes magnitude and phase of the rotor voltage command in a stationary reference frame.

Using the same approach like the grid side converter, the stator and rotor currents are transformed to the new reference frame using the voltage angle calculated in equation 4.2.

$$\begin{bmatrix} i^e{}_{sq} \\ i^e{}_{sd} \\ i^e{}_{s0} \end{bmatrix} = k_s(\theta) \begin{bmatrix} i_{sd} \\ i_{sq} \\ i_{s0} \end{bmatrix} \tag{4.8}$$

$k_s(\theta)$, is the Park's transformation matrix given in equation 4.4.

$$\begin{bmatrix} i^e{}_{rd} \\ i^e{}_{rq} \\ i^e{}_{r0} \end{bmatrix} = k_s(\theta_s) \begin{bmatrix} i_{rd} \\ i_{rq} \\ i_{r0} \end{bmatrix} \tag{4.9}$$

Where

θ_r, is the rotor angle and

$\theta_s = \theta - \theta_r$, is the slip angle

Stator flux linkage expressed in the new reference frame:

$$\begin{aligned} \lambda^e{}_{sd} &= L_s i^e{}_{sd} + L_m i^e{}_{rd} \\ \lambda^e{}_{sq} &= L_s i^e{}_{sq} + L_m i^e{}_{rq} \end{aligned} \tag{4.10}$$

Where, $L_s = L_{1s} + L_m$

Aligning the d-axis of reference frame to be along the line voltage will result in: $\lambda^e{}_{sd} = 0$ and neglecting stator resistance will lead to $V_{sq} = 0$.

Substituting for $V_{sq} = 0$, the active and reactive power will be simplified as follows:

$$P_s = \frac{3}{2}\left(V^e{}_{sd} i^e{}_{sd} + V^e{}_{sq} i^e{}_{sq}\right) = \frac{3}{2}(V^e{}_{sd} i^e{}_{sd})$$
$$Q_s = \frac{3}{2}(V^e{}_{sq} i^e{}_{sd} - V^e{}_{sd} i^e{}_{sq}) = \frac{-3}{2}(V^e{}_{sd} i^e{}_{sq}) \qquad (4.11)$$

Therefore, the above equations show that active and reactive powers of the stator can be controlled independently.

From Eq. 4.10,

$$\lambda^e{}_{sd} = L_s i^e{}_{sd} + L_m i^e{}_{rd} = 0$$

$$i^e{}_{sd} = \frac{-L_m}{L_s} i^e{}_{rd} \qquad (4.12)$$

Substituting for $i^e{}_{ds}$ into the torque and active power equation will result in:

$$T_e = \frac{-3}{2}\frac{p}{2}(\lambda^e{}_{sd} i^e{}_{sq} - \lambda^e{}_{sq} i^e{}_{sd}) = \frac{-3}{2}\frac{p}{2}\frac{L_m}{L_s}(\lambda^e{}_{sq} i^e{}_{rd}) \qquad (4.13)$$

$$P_s = \frac{3}{2}(V^e{}_{sd} i^e{}_{sd}) = -\frac{3}{2}\frac{L_m}{L_s}(V^e{}_{sd} i^e{}_{rd}) \qquad (4.14)$$

The stator magnetizing current is

$$\underset{i_{ms}}{\xrightarrow{\qquad}} = \frac{\lambda^e{}_{sd} + j\lambda^e{}_{sq}}{L_m}$$

$$\xrightarrow[i_{ms}]{} = \frac{j\lambda_{sq}}{L_m}$$

Thus, $\xrightarrow[i_{ms}]{} = | i_{ms} |$ is a constant value

From Eq 4.10,

$$i_{sq} = \frac{\lambda_{sq} - L_m i_{rq}}{L_s} = \frac{L_m}{L_s}(| i_{ms} | - i_{rq}) \tag{4.15}$$

$$Q_s = \frac{-3}{2}(V_{sd} i_{sq}) = \frac{-3}{2}\frac{l_m}{L_s} V_{sd}(| i_{ms} | - i_{rq}) \tag{4.16}$$

Thus, the variations in rotor currents will also reflect in the variation of stator side currents, $i^e{}_{sd}$ $i^e{}_{sq}$ and hence in the stator side real and reactive powers also. This principle has been used in the control of stator real and reactive powers. The control scheme uses a PI controller to obtain the reference value for $i^e{}_{rd}$ from real power error that is the difference between desired and actual values of real power as shown in fig. 4.5. Similarly, a PI controller can be tuned to get the reference value for $i^e{}_{rq}$ from the reactive power error. Then, both reference currents were transformed to their natural reference frame that is the rotor frame. These rotor current references, after a dq-to-abc transformation, were used for implementing the technique on the rotor side three-phase converter.

Using the supply-voltage vector reference frame, a simple and smooth connection of the stator windings to the line grid can be performed during the start-up procedure of the DFIM-based system.

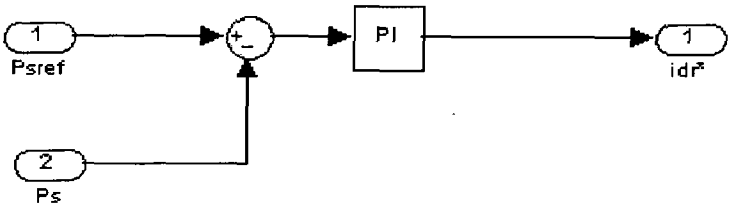

Fig.4.5 Reference Current from Active Power Error

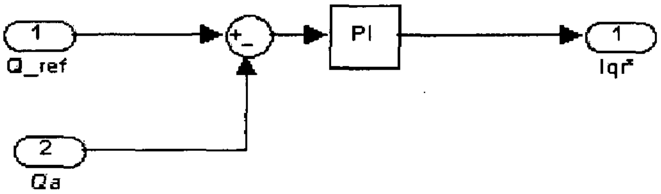

Fig.4.6 Reference Current from Reactive Power Error

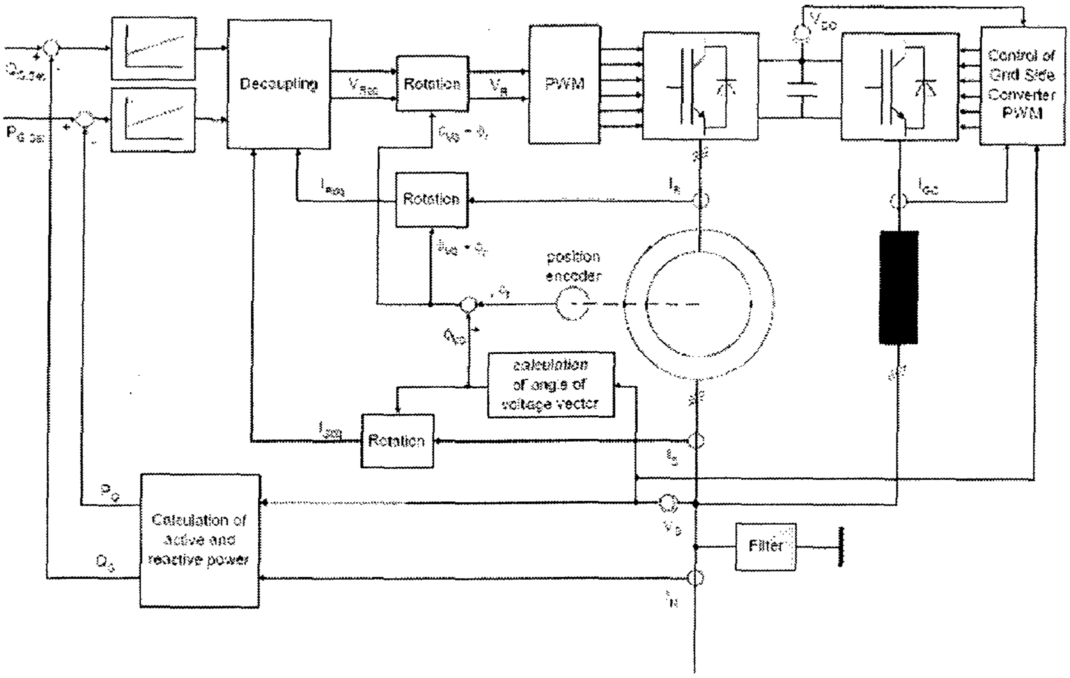

Fig. 4.7 Vector Controller Diagram for the Rotor Side Converter from [24]

5. IMPLEMENTATION OF THE MODEL IN MATLAB/SIMULINK

This study is made with simulation on the Matlab/Simulink and Power System Block Set modules. The induction machine is modeled on the stationary reference frame. Because of the transient studies of adjustable-speed drives, stationary reference frame is usually more convenient than synchronously rotating reference frame, which is appropriate for power system studies. With stationary reference frame, the speed of the reference frame is equal to zero. Stator and rotor voltage equation, flux linkage equation and torque equation are utilized for modeling in term of q component, d component and zero component. Stator and rotor circuits are assumed to be star connected. In addition, all rotor parameters are transformed to stator side via stator-rotor turns ratio (in this study a turn ratio of 1 is assumed).

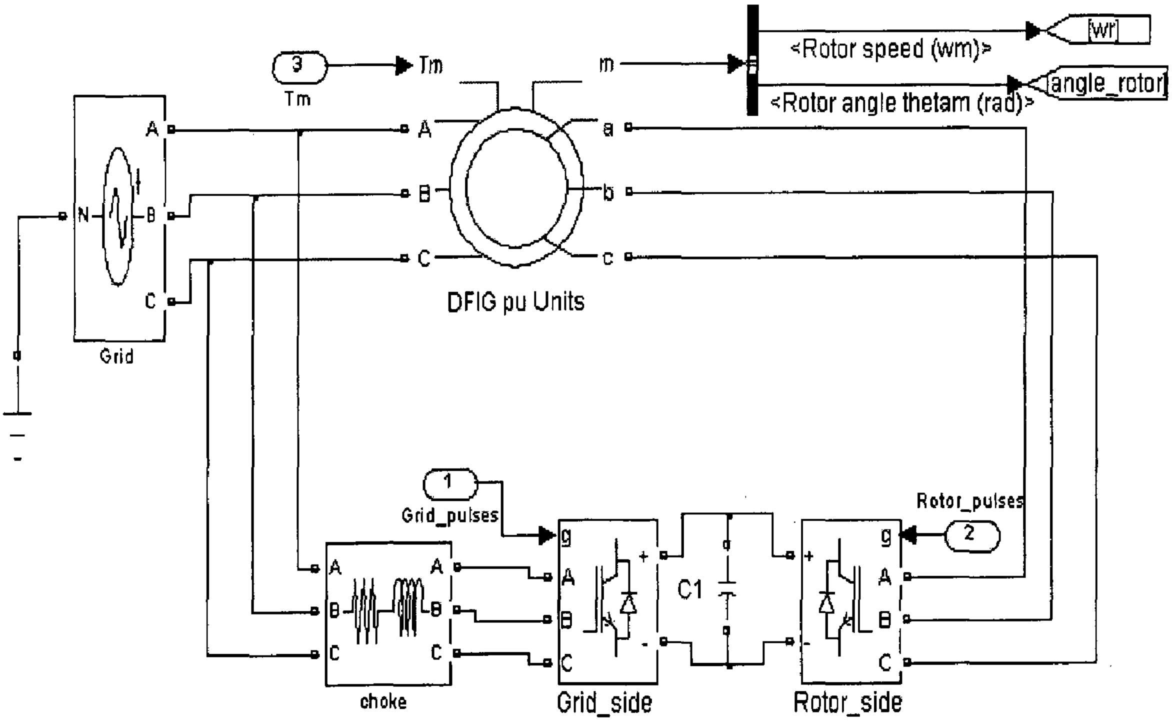

Fig.5.1 Simulink Model of Grid Connected DFIG

Two vector-control schemes are designed for the rotor-side and grid-side PWM converters using the technique explained in chapter 4. The objective of the vector-control scheme for the grid-side PWM converter is to keep the DC-link voltage constant regardless of the magnitude and direction of the rotor power.

Using equations 4.1 to 4.6, the matlab/simulink model for the grid-side converter is shown in Fig. 5.2. Good tracking characteristics are obtained without adding compensation terms (equation 4.7).

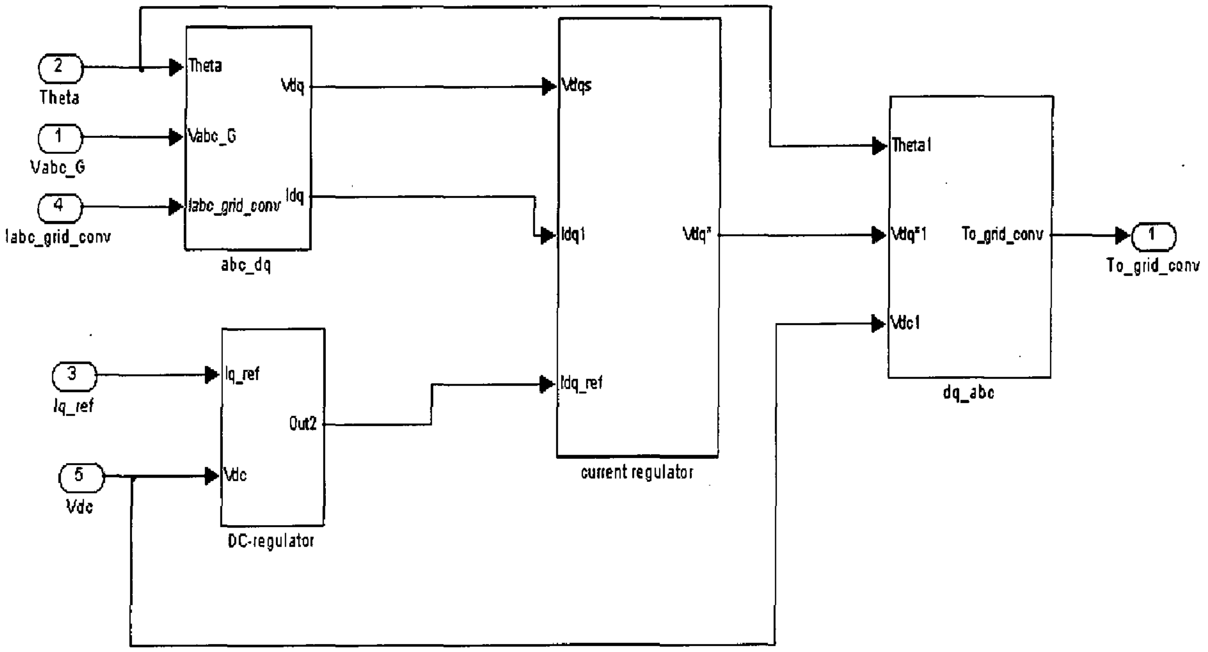

Fig.5.2 Grid-side Converter simulink Model

The reference current, $i^{e}_{gd,ref}$, for the DC bus regulator is obtained by comparing the actual and reference DC voltages and using a standard PI regulator. To make the displacement factor unity, $i^{e}_{gq,ref}$ is forced to zero.

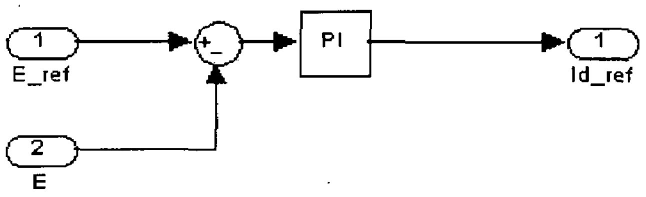

Fig. 5.3 Refernce Current From Dc Link Voltage Error

The vector-control scheme for the rotor-side PWM converter ensures decoupling control of stator-side active and reactive power drawn from the grid. The reference value of the stator-side active power $P_{s,ref}$ is obtained via a look-up table for a given generator rotor speed, which enables the optimal power tracking for maximum energy capture from the wind. It also provides the generator with wide speed-range operation.

Using equations 4.1, 4.2, 4.8-4.16, the matlab/simulink block model for the rotor side converter is shown in Fig. 5.4

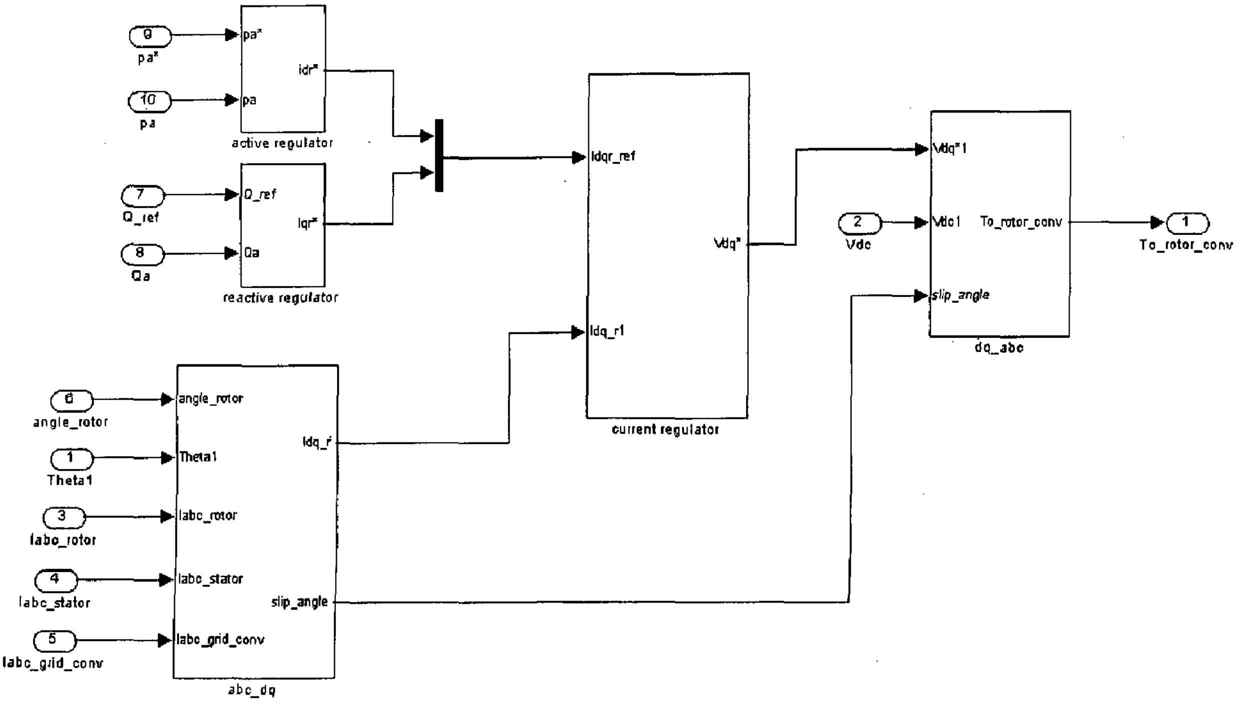

Fig . 5.4 Rotor Side Converter Simulink Model

$i^{e}_{rd,ref}$ and $i^{e}_{rq,ref}$ are obtained by comparing the actual and reference active and reactive powers, and using a PI controller to reduce the error to zero.

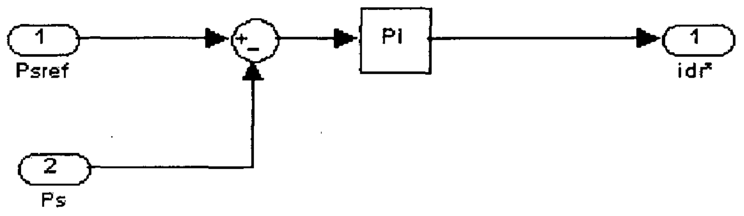

Fig. 5.5 $i^{e}_{rd,ref}$ Current from Active Power Error

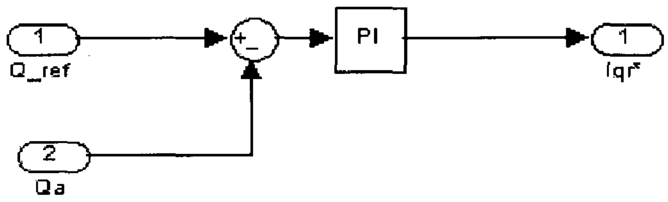

Fig.5.6 $i^{e}_{rq,ref}$ Current from Reactive Power Error

Turbine Tracking Characteristics

The power captured by the wind turbine is converted into electrical power by the induction generator and it is transmitted to the grid by the stator and the rotor windings. The turbine power-speed characteristics under consideration for the simulation purpose is shown in Fig. 5.7 for different wind speeds. The maximum turbine output power at base wind speed is 0.75 p.u of mechanical power. The base wind speed is the mean value of the expected wind speed. This base wind speed produces a mechanical power which is usually lower than the turbine nominal power. The turbine speed at this base wind speed reflected to the generator side is 1.2 p.u of nominal generator speed. At a speed greater than the synchronous speed, power is extracted from both the stator and rotor.

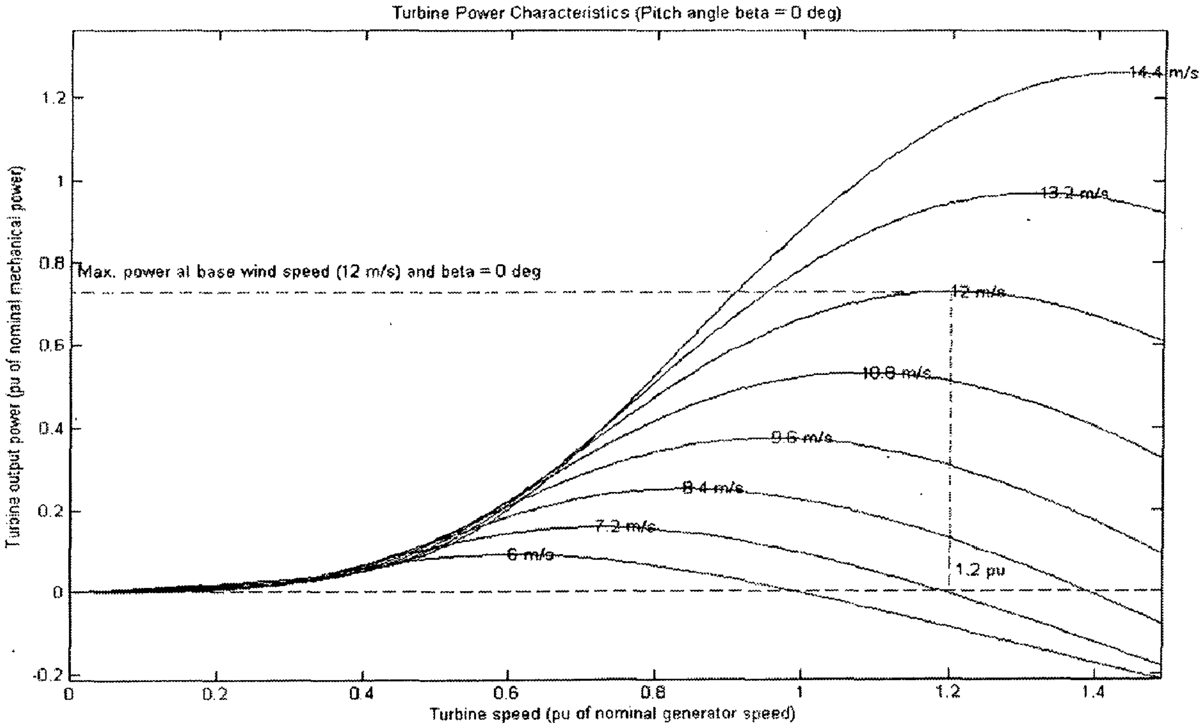

Fig. 5.7 Turbine Power Speed Characteristics

The rotor-side converter is used to control the wind turbine output power and the voltage measured at the grid terminals. The power is controlled in order to follow a pre-defined power-speed characteristic, named tracking characteristic. This characteristic is illustrated by the ABCD curve in Fig. 5.8 superimposed to the mechanical power characteristics of the turbine obtained at different wind speeds. The actual speed of the turbine w_r is measured and the corresponding mechanical power of the tracking characteristic is used as the reference power for the power control loop. The tracking characteristic is defined by four points: A, B, C and D. From zero speed to speed of point A the reference power is zero. Between point A and point B the tracking characteristic is a straight line. Between point B and point C the tracking characteristic is the locus of the maximum power of the turbine (maxima of the turbine power vs turbine speed curves). The tracking characteristic is a straight line from point C and point D. The power at point D is one per unit (1 p.u.). Beyond point D the reference power is a constant equal to one per unit (1 p.u.).

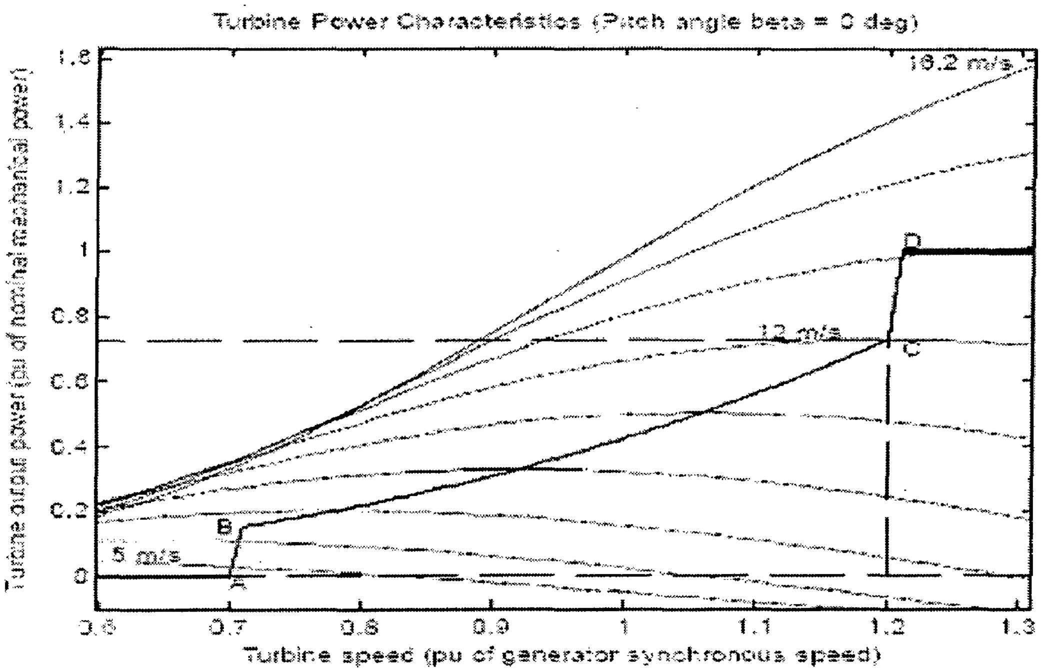

Fig.5.8 Turbine Characteristics and Tracking Characteristics

The tracking characteristic obtained through a look up table for different turbine speed w_r by interpolation-extrapolation is shown Fig. 5.9 [25].

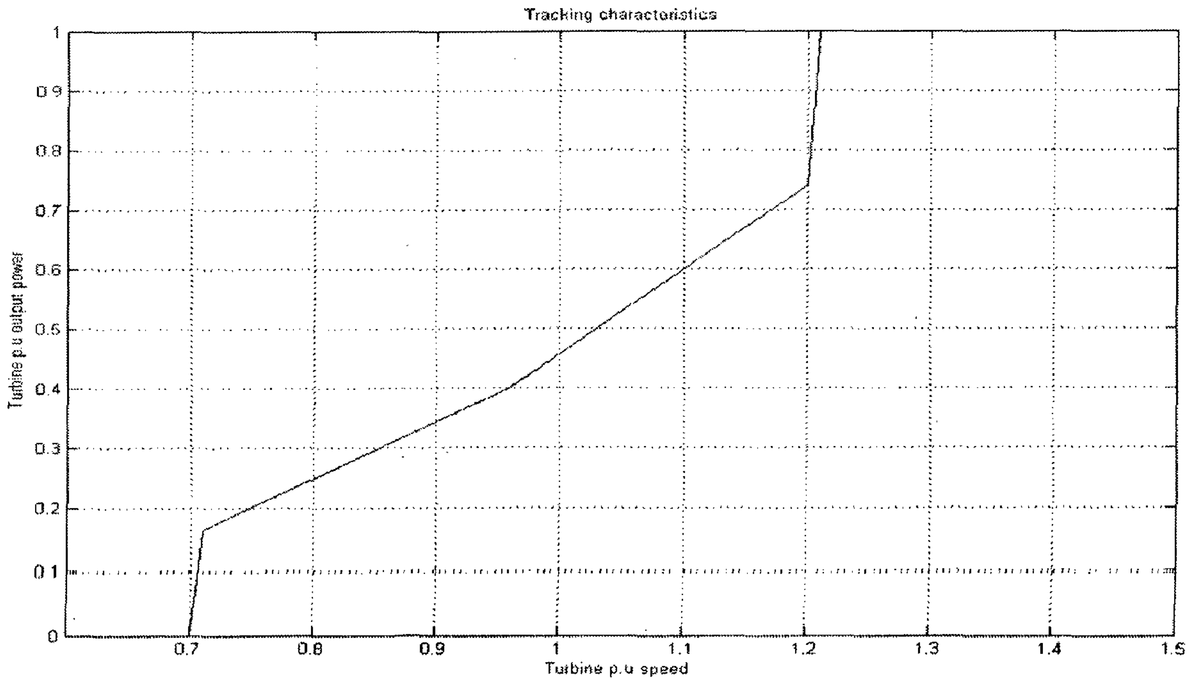

Fig. 5.9 Tracking Characteristics Obtained By Look-Up Table

The pitch angle is kept constant at zero degree until the speed reaches point D speed of the tracking characteristic. Beyond point D the pitch angle is proportional to the speed deviation from point D speed. The wind speed should be selected such that the rotational speed is less than point D speed.

The simulink model of the wind turbine, optimal power tracking and pitch angle control is shown in Fig.5.10. The inputs to the wind turbine block are Generator speed w_r , pitch angle (beta) and wind speed. The model calculates the p.u torque which is input to the generator. The second block calculates the optimum power (P_{opt}) from the turbine speed through look-up table. The third block is used to generate the pitch angle beta.

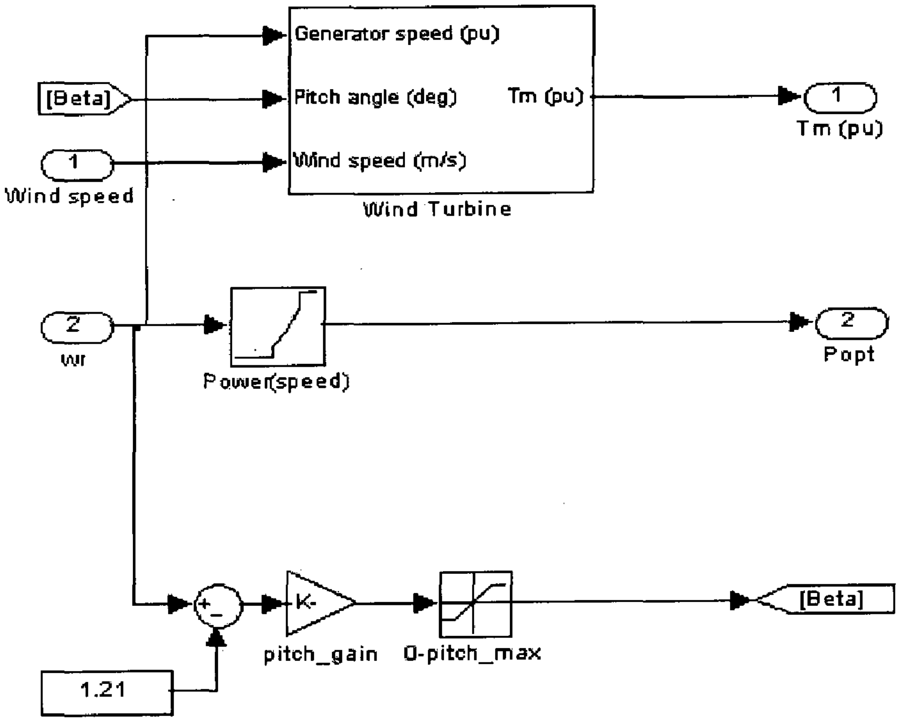

Fig. 5.10 Simulink Model of Wind Turbine and Pitch Angle Control

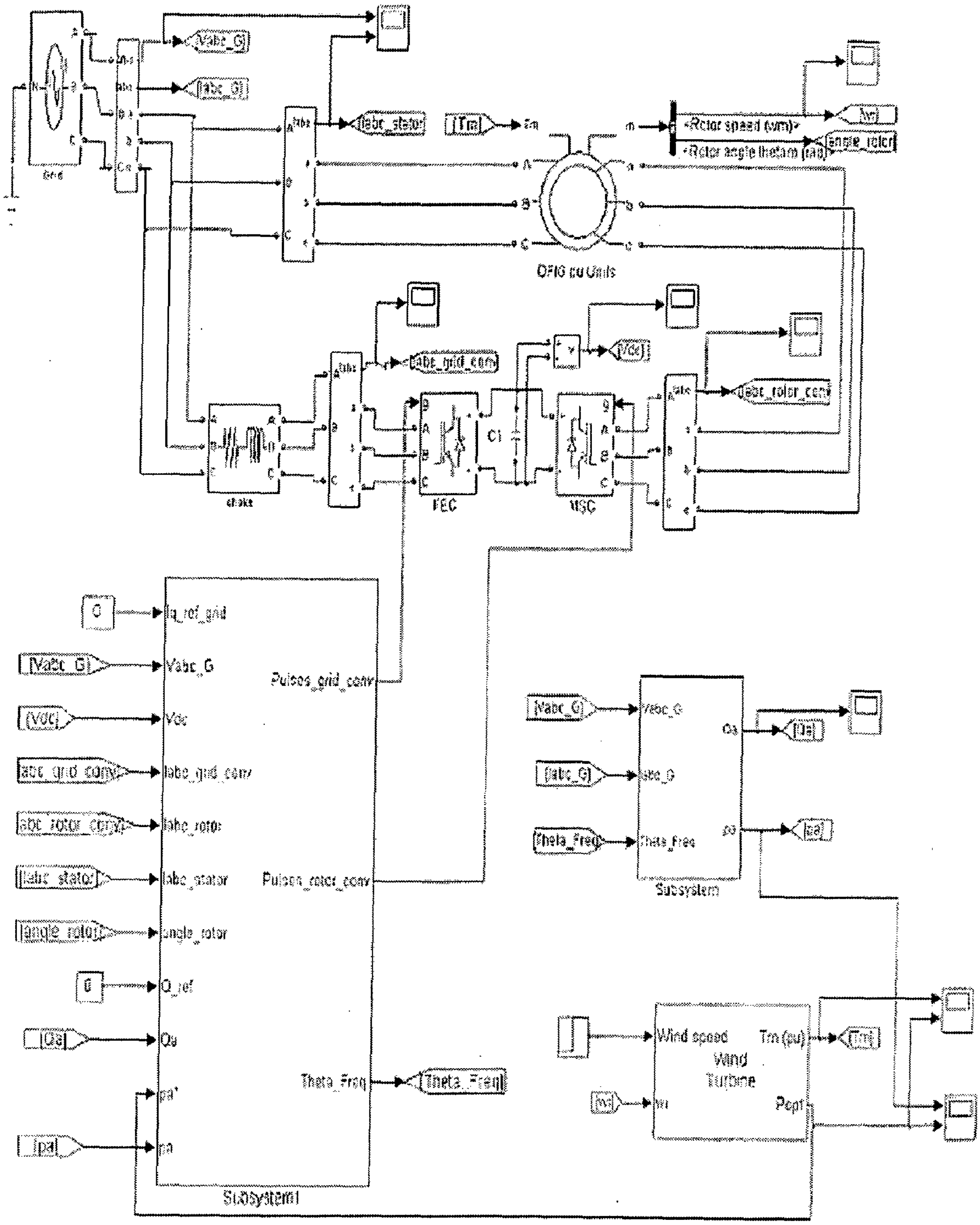

Fig. 5.11 Simulink Model of the Main Circuit Containing DFIG, Wind Turbine and Power Converter for Variable Speed Wind Power Generation

6. RESULTS AND DISCUSSIONS

For the analysis of these results, a wound rotor Induction machine and wind turbine with the specifications given in Appendix B has been used. The DFIG for variable speed wind power generation using vector control technique is implemented in Matlab/Simulink, which is the most popular and powerful tool for simulation. The various waveforms plotted are shown in this chapter.

Figures 6.1 to 6.8 shows the independent control of active and reactive power using vector control for a unit step change in both active and reactive power reference values without the wind turbine (the x- axis is time in sec).

I. Step change of 0.4 p.u in active power keeping the reactive power 0

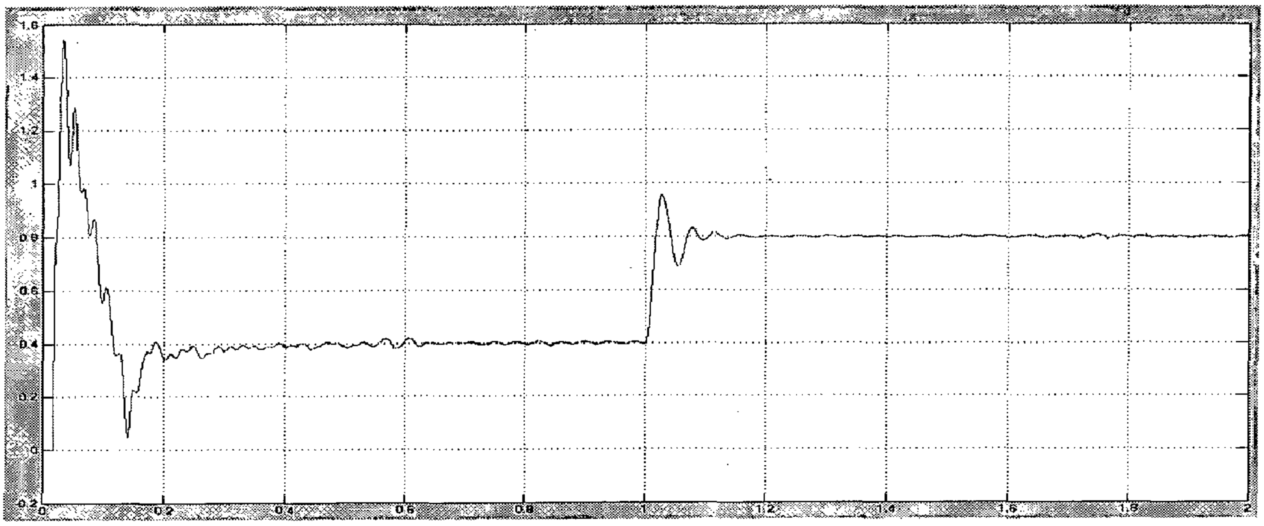

Fig. 6.1 Response of the System for Step Change in Active Power

From the above figure, it can be observed that the active power is controlled independently for an external active power input.

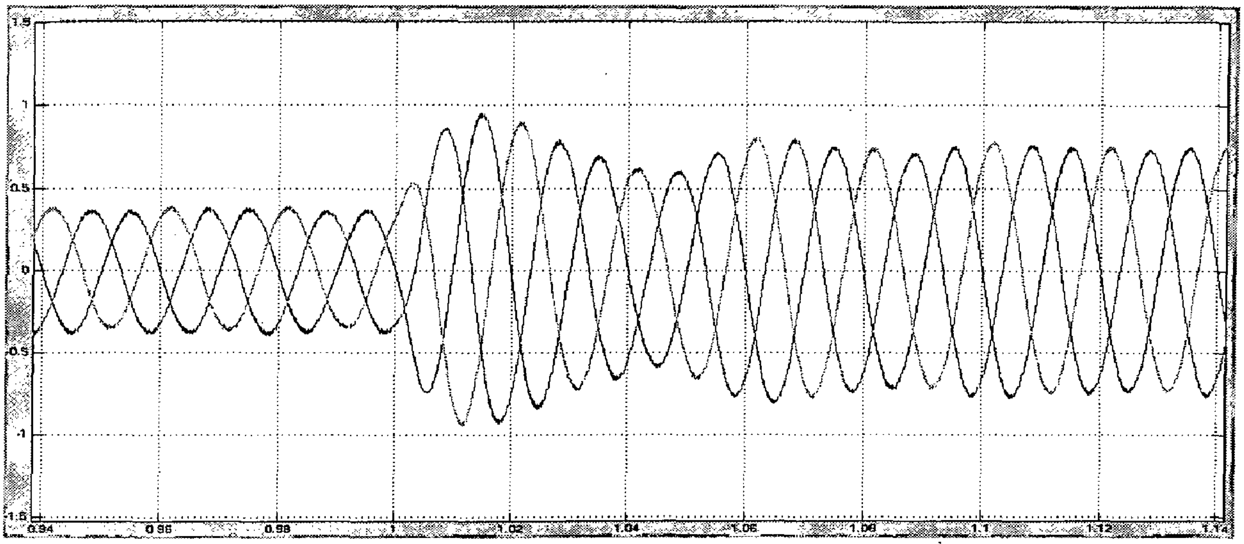

Fig. 6.2 Change in Stator Currents for a Step Change in Active Power

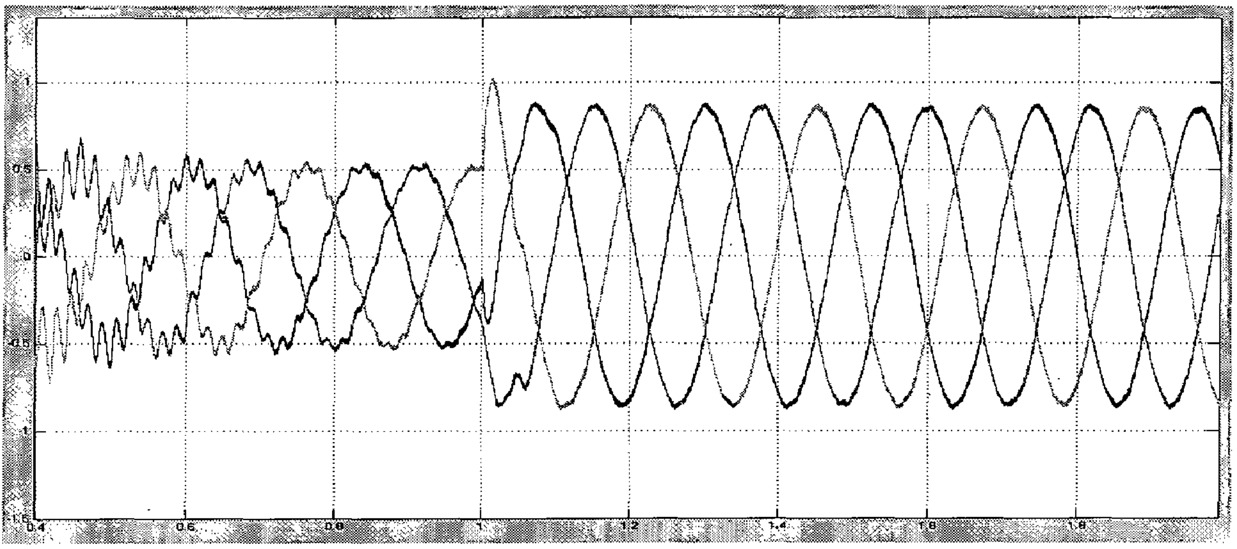

Fig. 6.3 Change in Rotor Currents Due to Step Change in Active Power

The above figures (6.2 and 6.3) show the change in stator current and rotor current for a unit step change in active power. The frequency of the rotor is the slip of the machine times the stator frequency.

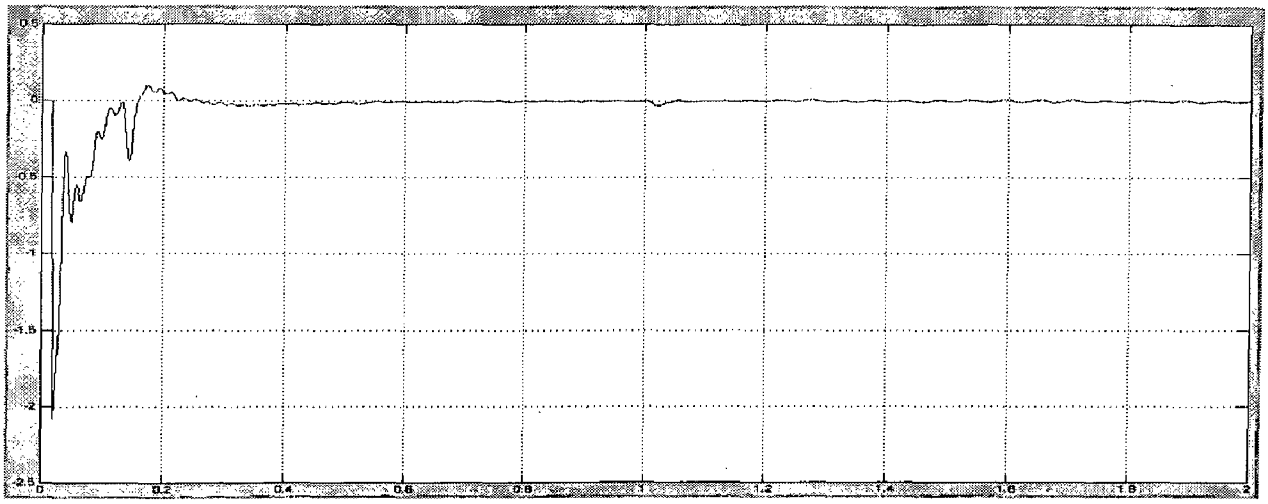

Fig. 6.4 Reactive Power for Unit Step Change in Active Power

The measured reactive power is kept at zero for zero external reference input and for a unit step change in active power as shown in the above figure (6.4).

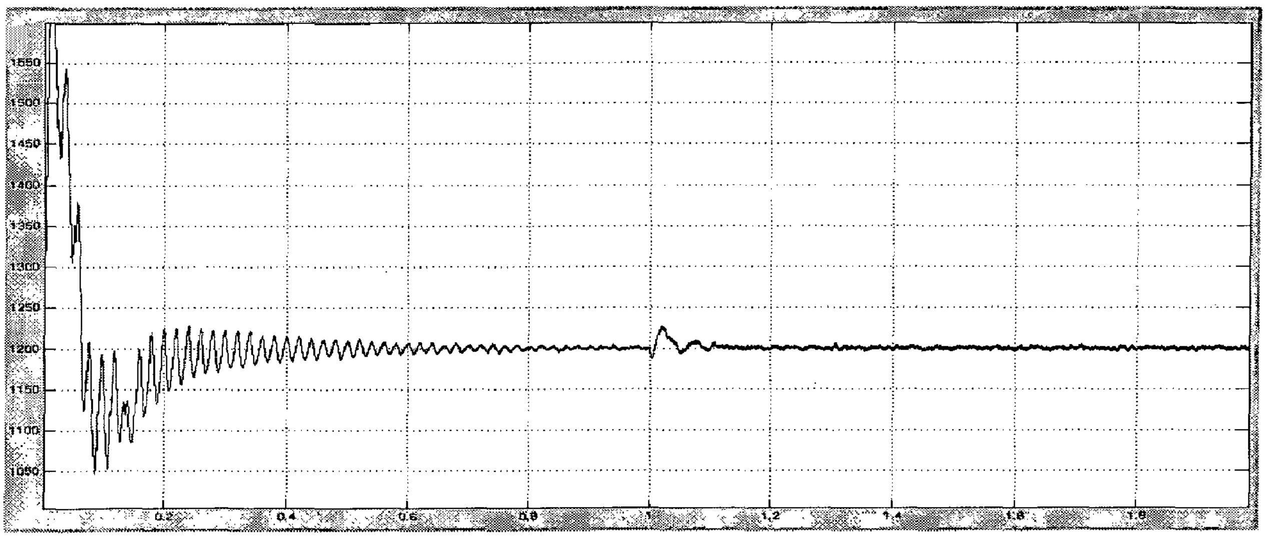

Fig. 6.5 DC Link Voltage for Step Change in Active Power

From the above figure, it can be seen that the DC link voltage is held constant in spite of change in active power.

II. Step change in reactive power keeping active power at 0.4 p.u

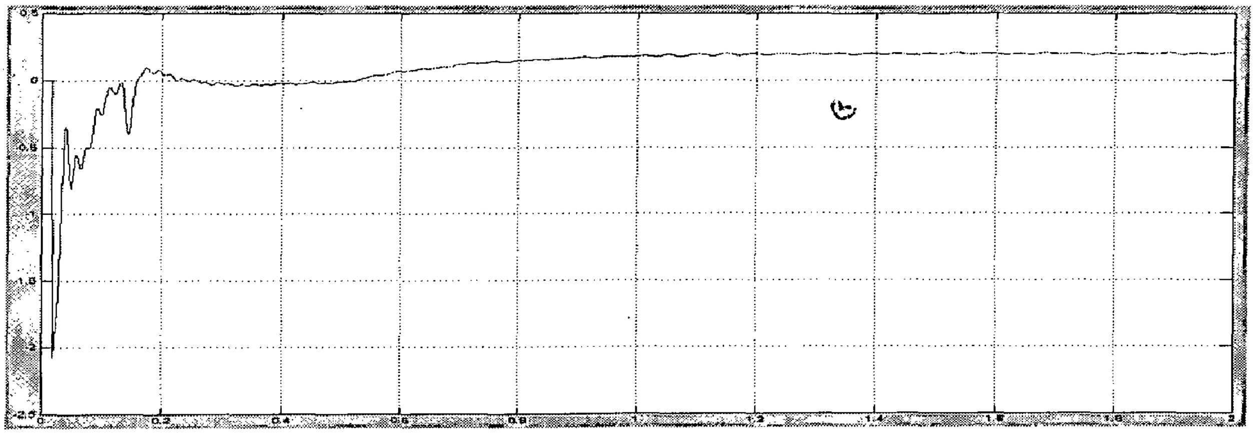

Fig. 6.6 Response of the System for a Step Change in Reactive Power

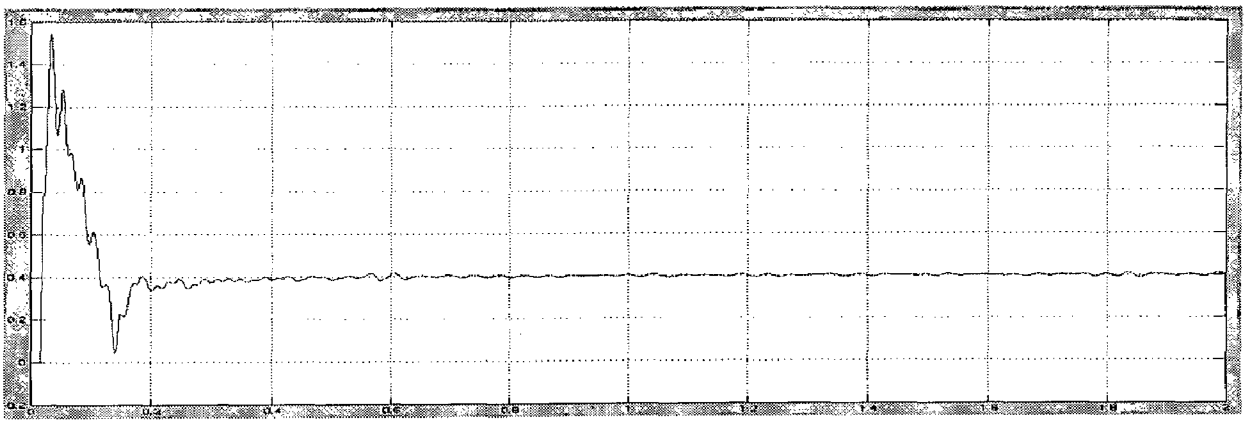

Fig. 6.7 Actual Active Power for a Step Change in Reactive Power

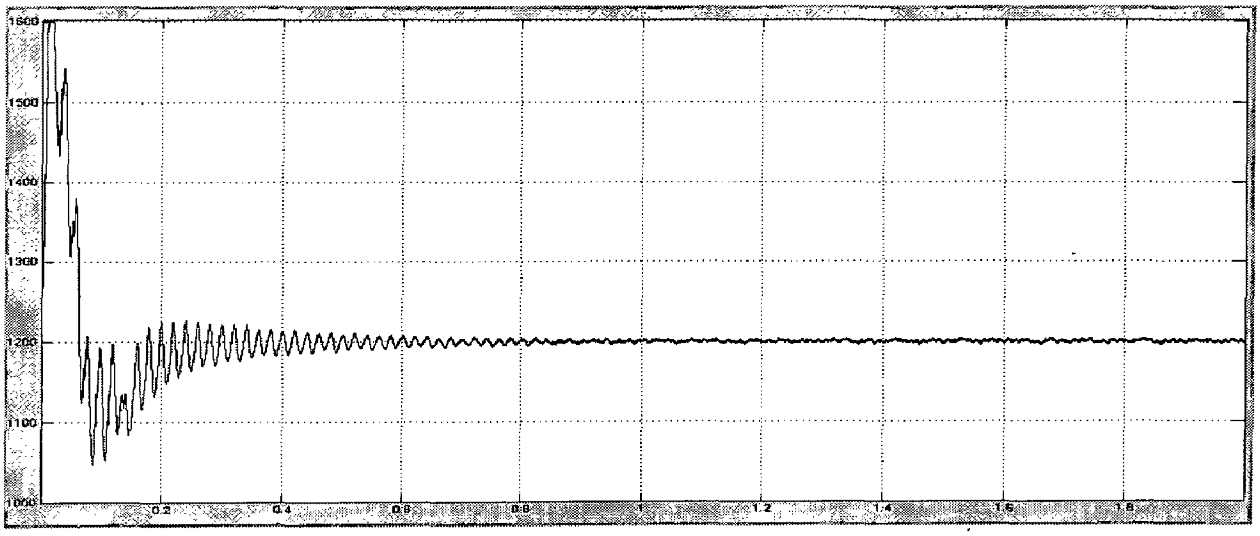

Fig. 6.8 DC Link Voltage for a Step Change in Reactive Power

III. Vector control for variable speed wind power generation

a. Sub-synchronous generation

Figures 6.9 to 6.17 show response of the system when the wind speed changes from 8 to 10.6 m/s.

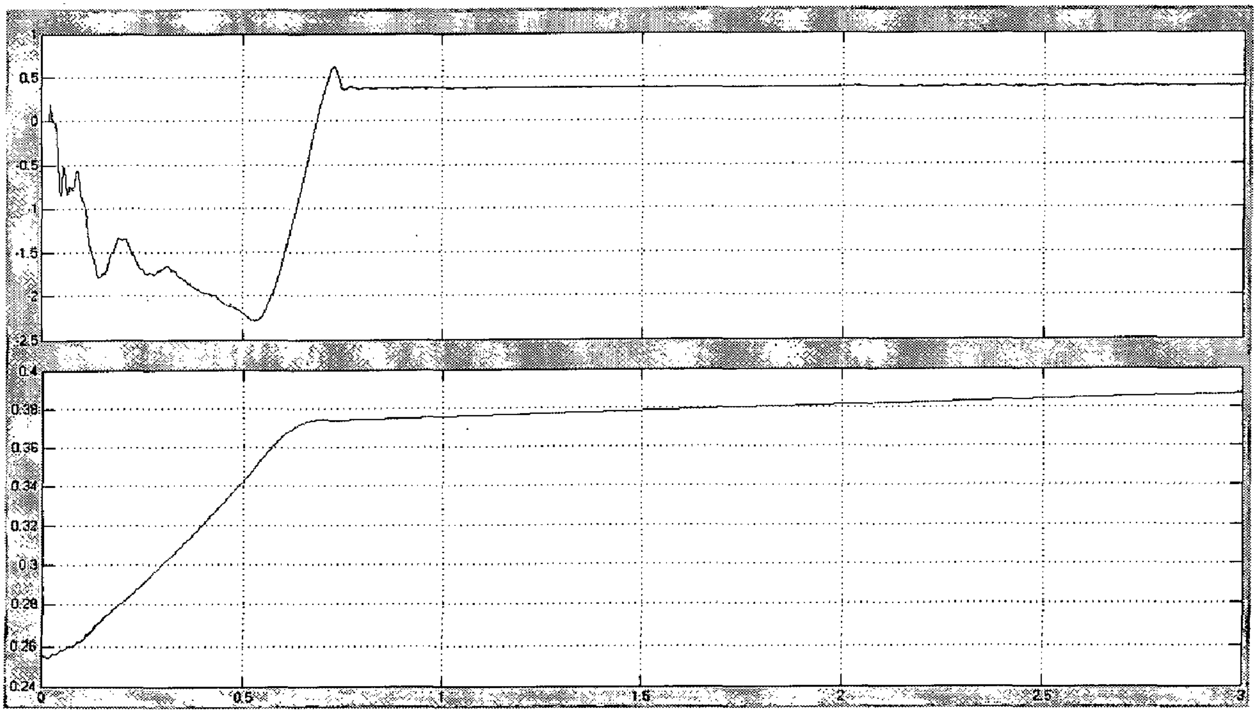

Fig. 6.9 Actual Active Power (P_s, upper figure) and Reference Active Power ($P_{s,ref}$, lower figure)

From the above figure, it can be seen that the measured active power at the grid terminal and the reference active power from the optimal tracking are the same at steady state.

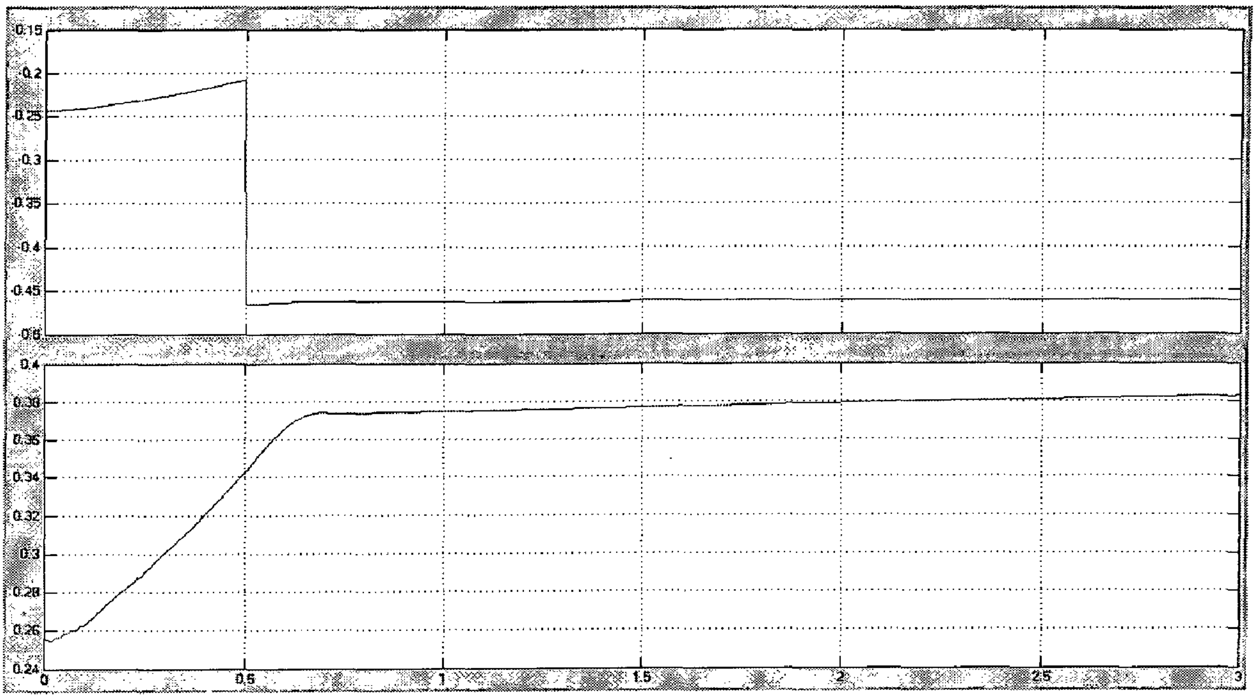

Fig. 6.10 Output Torque (T_m, upper) from the Wind Turbine and Reference Active Power ($P_{s,ref}$, lower) from Optimal Power Tracking

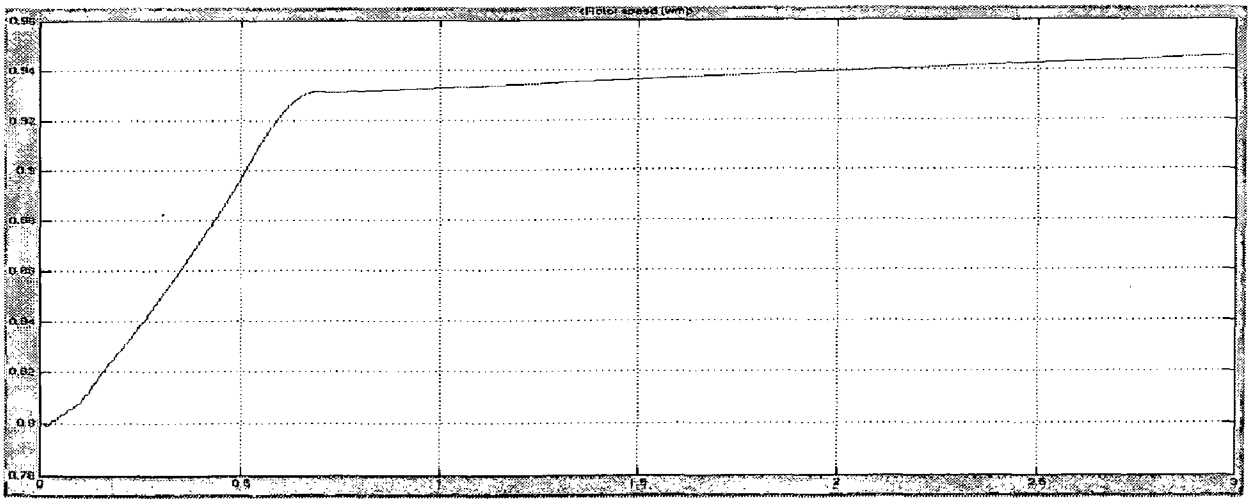

Fig. 6.11 Generator Speed (w_r)

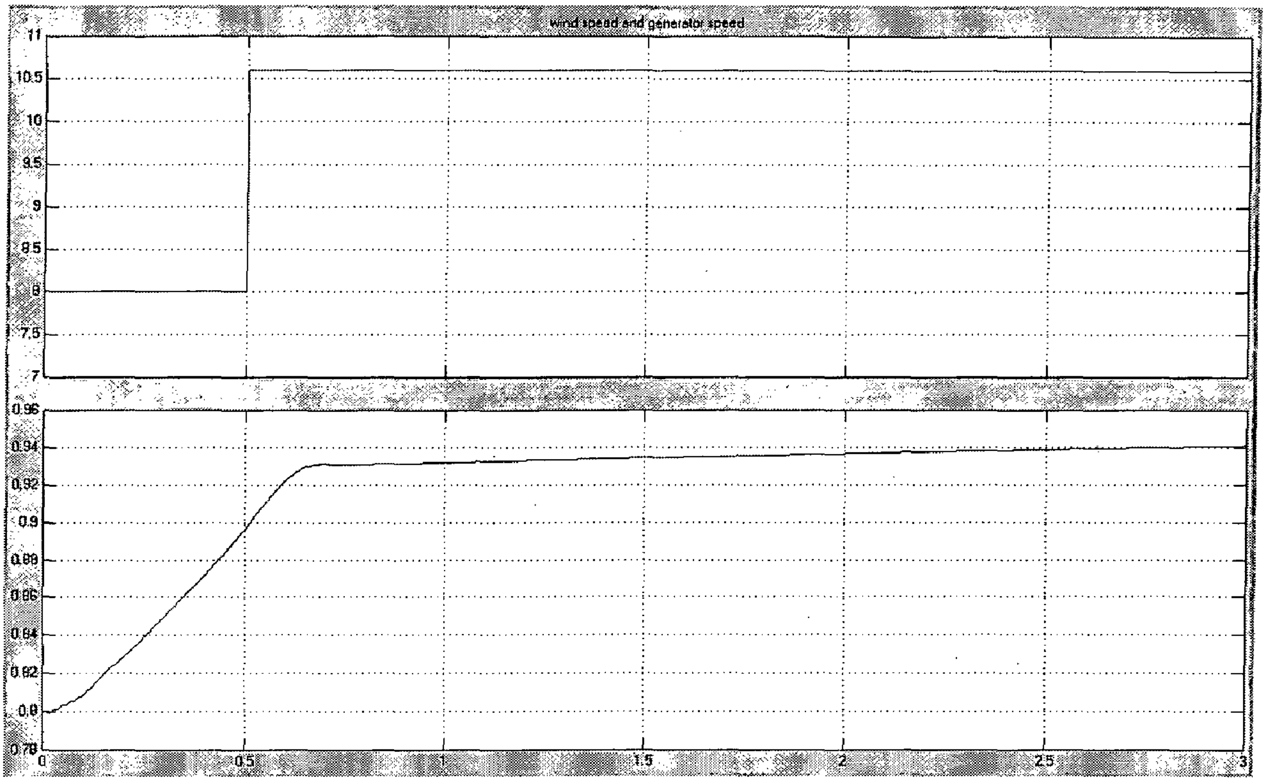

Fig. 6.12 Wind Speed (upper) Vs Generator Speed (lower)

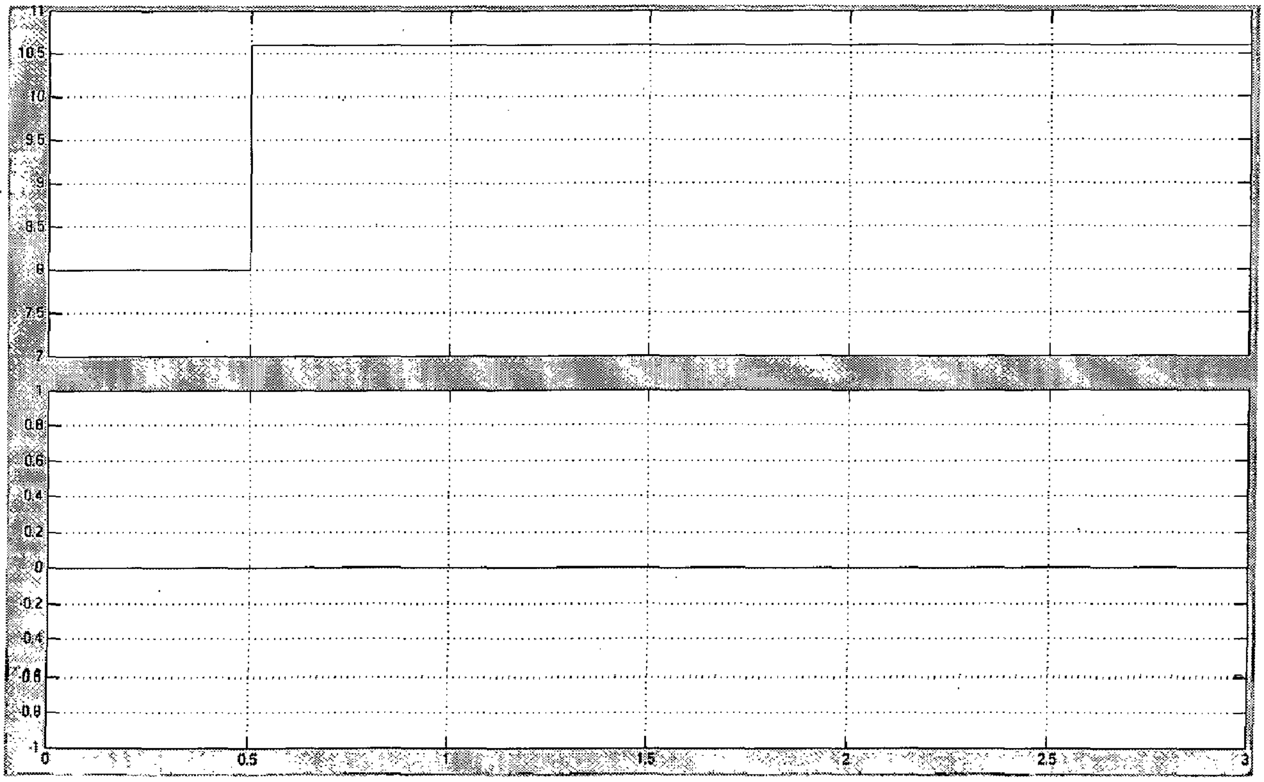

Fig. 6.13 Wind Speed (upper) Vs Pitch Angle (lower)

From the above graph, we can see that the pitch angle is kept constant at its maximum value (zero) for sub-synchronous generation where the output power is below the rated value.

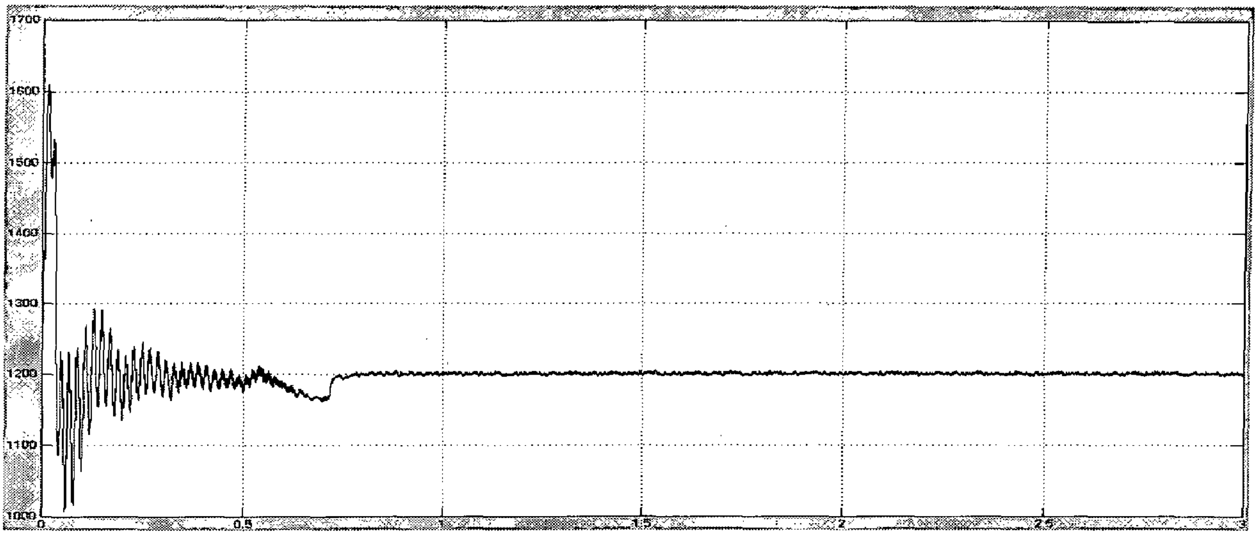

Fig. 6.14 Dc Link Voltage

From the above figure, it can be seen that the DC link voltage is held constant.

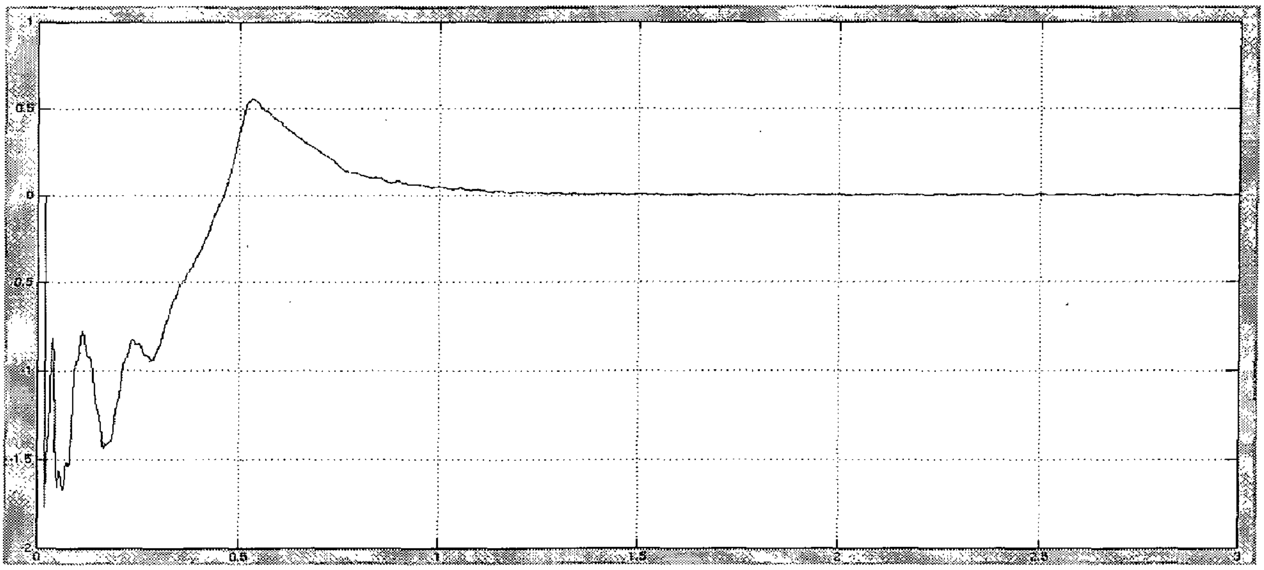

Fig. 6.15 Actual Reactive Power Q_s When Reference Reactive Power ($Q_{s,ref}$) is Zero

The measured reactive power and the reference reactive power are both zero at steady state as seen in the above figure.

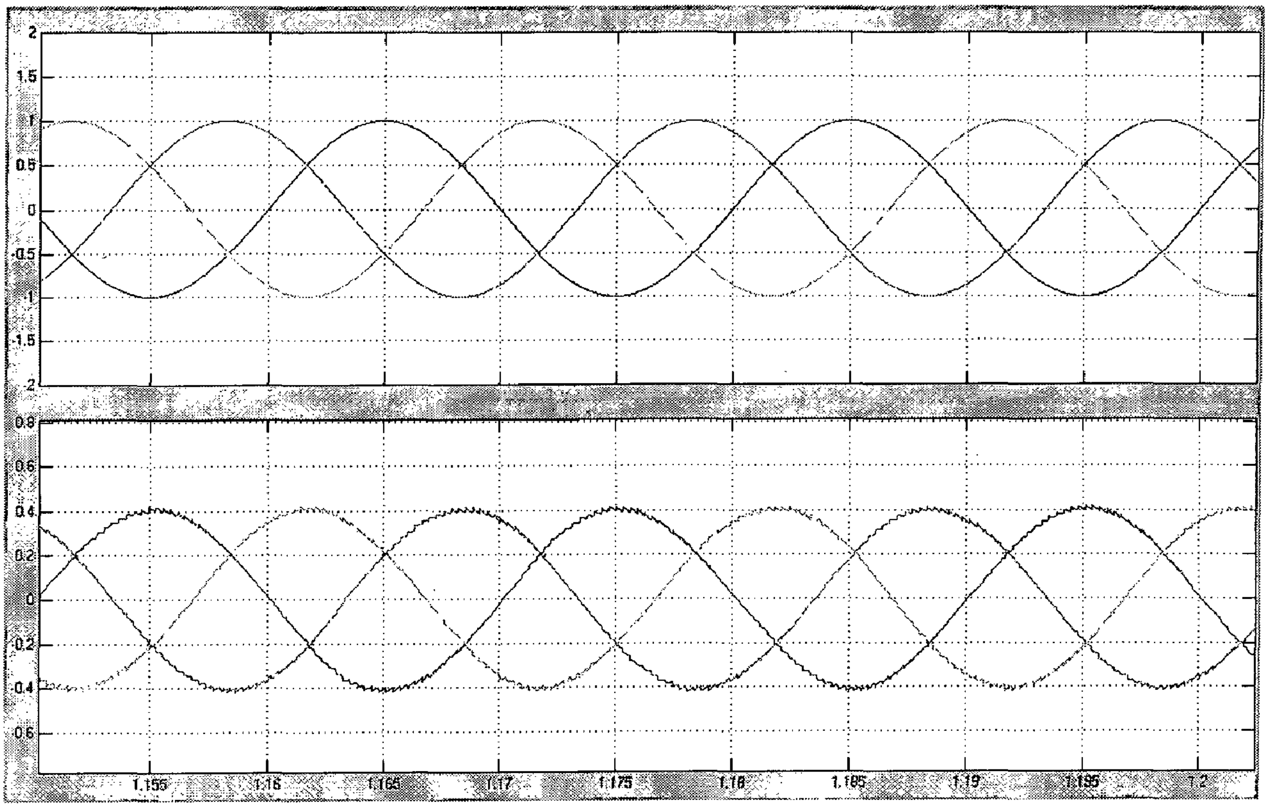

Fig. 6.16 Stator Voltages (upper) and Currents (lower)

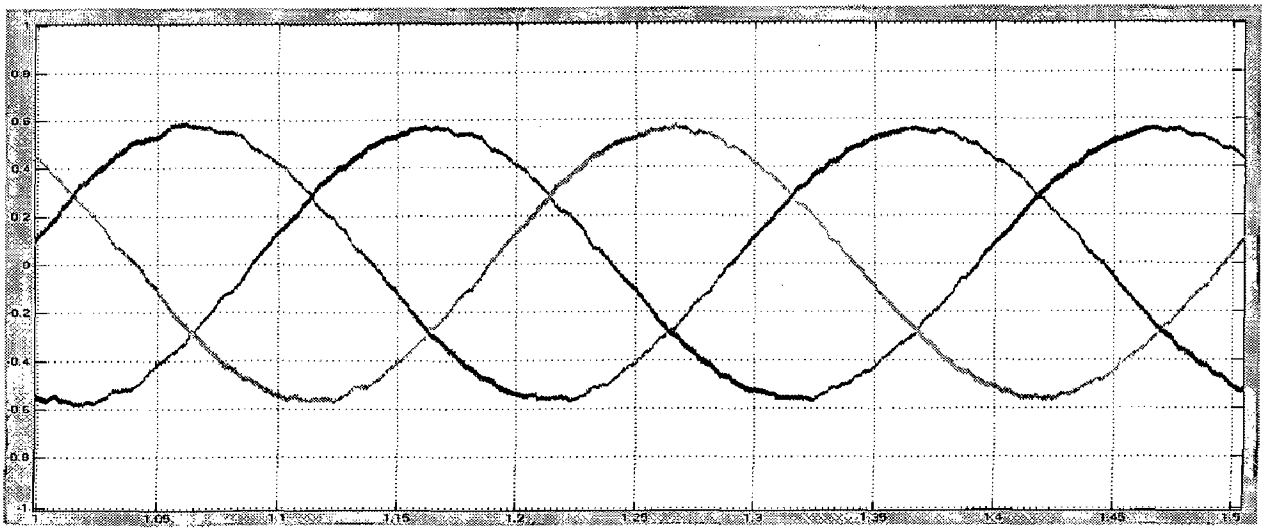

Fig. 6.17 Rotor Currents

Figures 6.16 and 6.17 show that the frequency of the rotor is the slip times the stator frequency

b. Super-synchronous generation (1.2 p.u and above)

Figures 6.18 to 6.23 show the response of the system for super-synchronous generation.

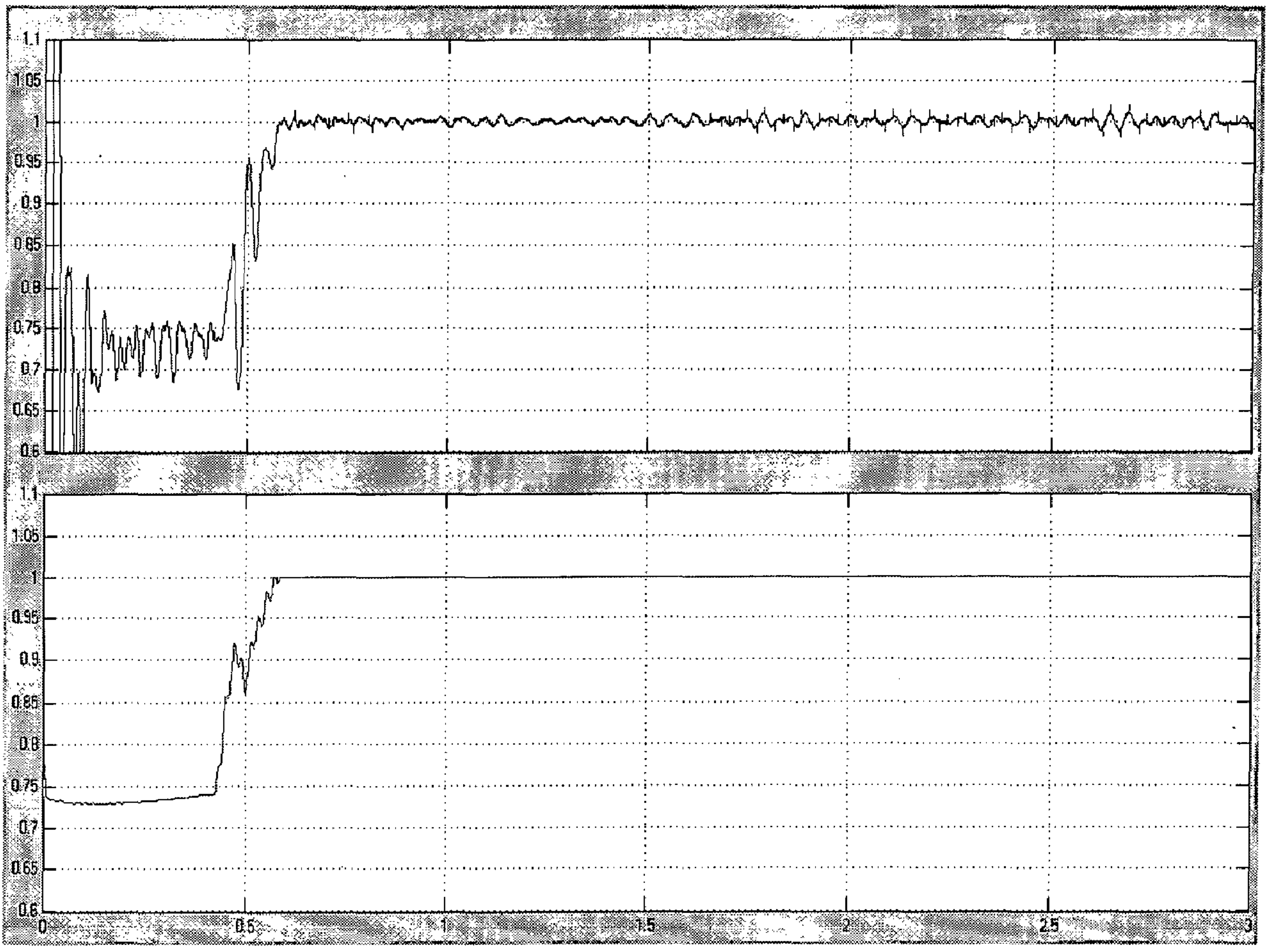

Fig. 6.18 Actual Active Power (P_s, upper) and Reference Active Power ($P_{s,ref}$, lower)

Like sub-synchronous generation, the measured active power at the grid terminal and the reference active power from the optimal tracking have the same characteristics and are limited to the rated value (1 p.u) as seen in figure 6.18.

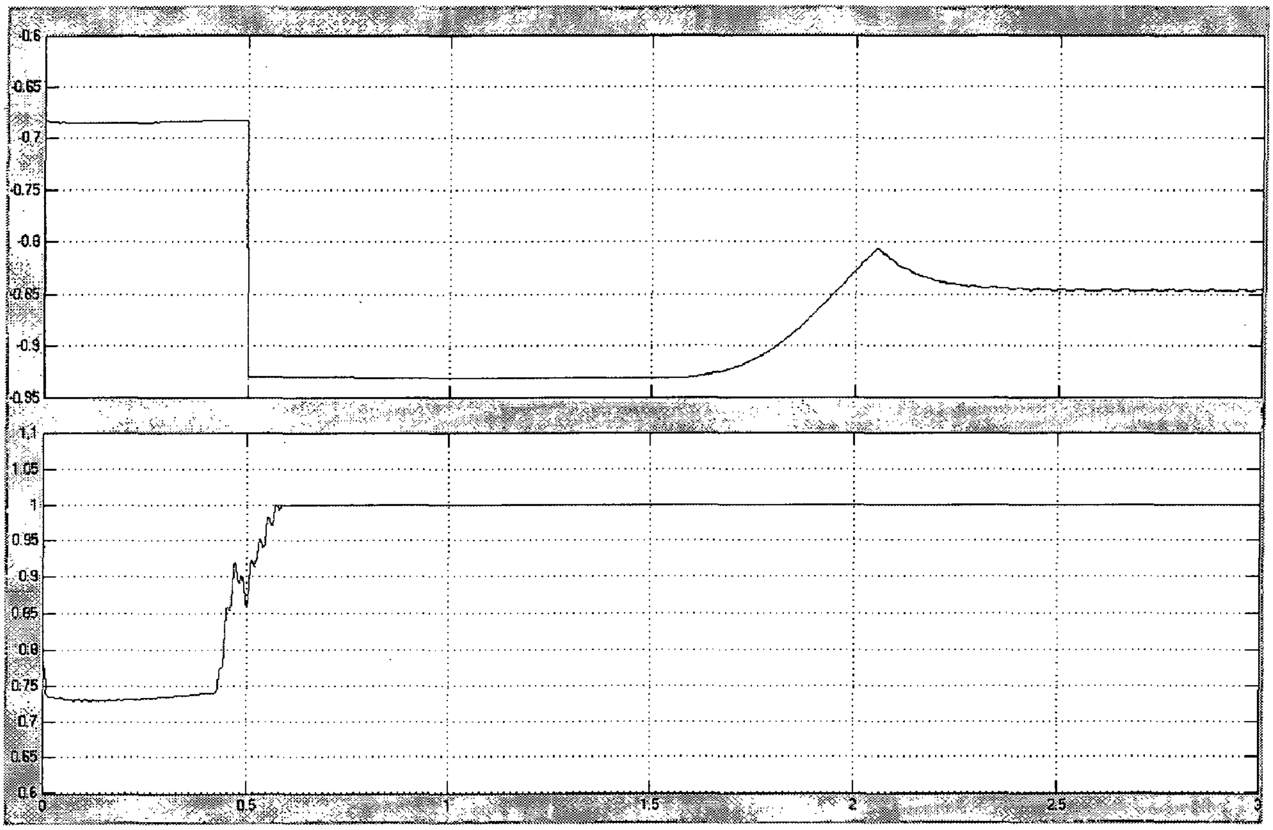

Fig. 6.19 Output Torque (T_m, upper) from the Wind Turbine and Reference Active Power ($P_{s,ref}$, lower) From Optimal Power Tracking

From the above figure, it can be observed that the output torque is limited because the pitch angle is called in to action since from the tracking characteristics (Fig.5.8) the output power corresponding to the wind speed is above the rated value.

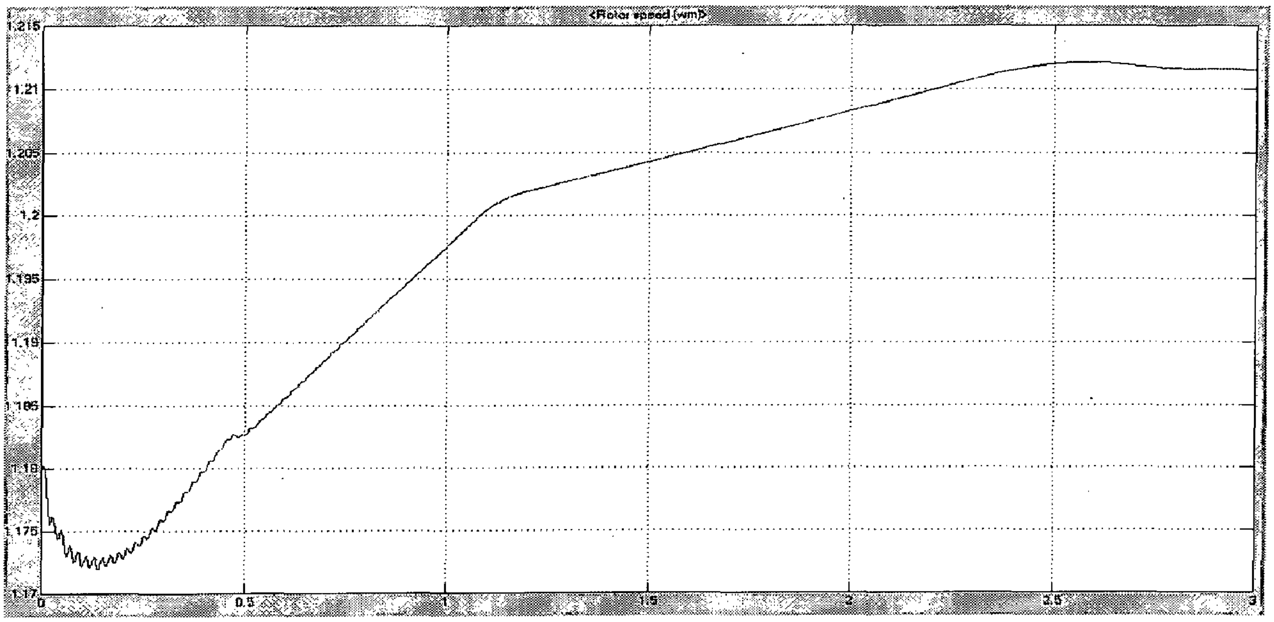

Fig. 6.20 Generator Speed (w_r)

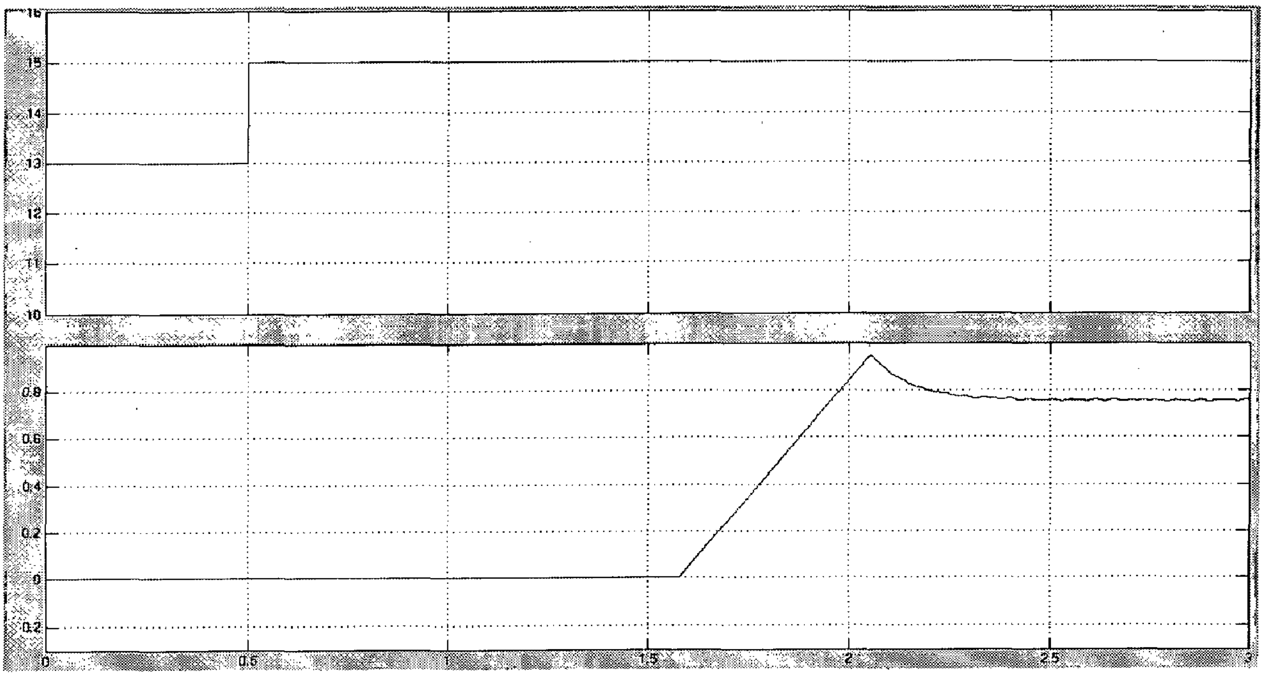

Fig. 6.21 Wind Speed (upper) Vs Pitch Angle (lower)

From the above figure, it can be seen that the pitch angle control is called in to action when the generator speed is above 1.21 p.u. The pitch angle limits the output power and torque.

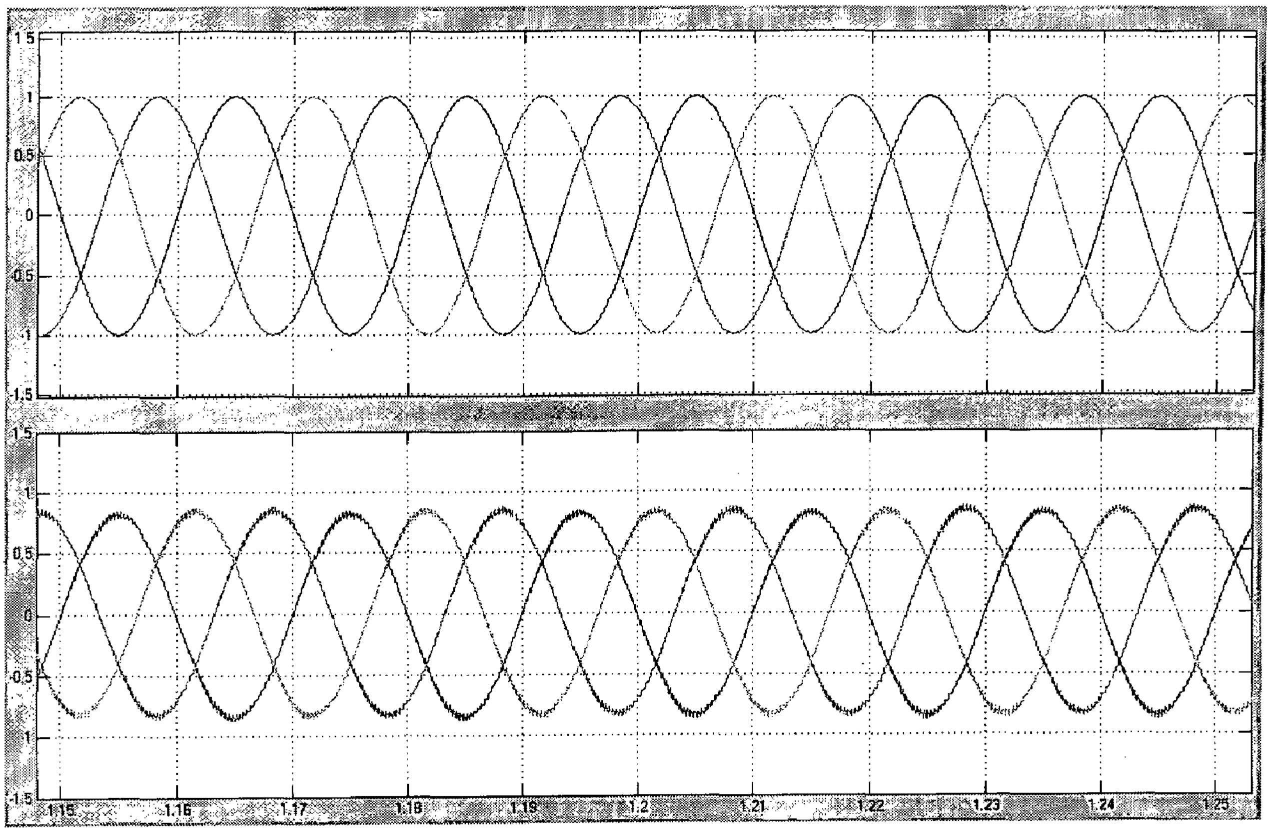

Fig. 6.22 Stator Voltages (upper) and Currents (lower)

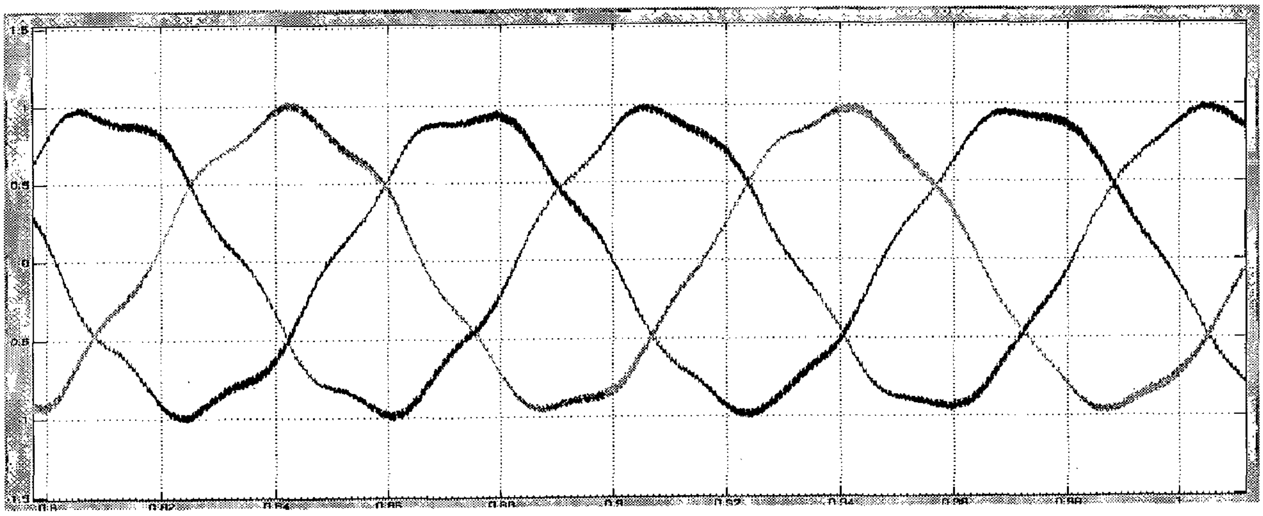

Fig. 6.23 Rotor Currents

7. CONCLUSIONS AND SCOPE OF FUTURE WORK

Induction machines are commonly used for wind power generation using wind turbines. Squirrel cage Induction machines are used either at fixed speed or variable speed wind turbines. It is shown that a variable speed system using wound rotor induction machine controlled from the rotor side is superior because of higher energy output, lower rating (hence, lower cost) of converters, and better utilization of a generator when compared to systems using a cage rotor induction machine with the same rating.

In the present work, vector control of grid connected DFIG for variable speed wind power generation has been done. A wound rotor induction machine with back-to-back three phase power converter between its rotor and the grid forms the electrical system. The stator is directly connected to the grid. Two vector-control schemes are designed for the rotor-side and grid-side PWM converters using line (supply) voltage oriented reference frame. The schemes make use of the supply voltage angle determined dynamically to map all the stator and rotor quantities onto the new reference frame. A complete matlab/simulink model has been developed for the independent control of active and reactive powers of the doubly fed generator under sub-synchronous and super-synchronous speed operation. Power extracted from the stator is supplied to grid but slip power is given to the rotor during sub-synchronous speed. During super-synchronous speed both power extracted from the stator and rotor are supplied to the grid.

From the simulation results, it has been observed that vector control scheme for the grid side converter keeps the DC link voltage constant irrespective of the direction of power flow and vector control scheme for the rotor side converter is used to independently control the stator active and reactive power hence torque and flux. For this, a control strategy has been used to control the stator current from the rotor current. The vector controller for the rotor side has been embedded in an optimal tracking using a look-up table for a given generator speed to capture the maximum energy from the wind. It has been shown from the simulation results that the reference active power from the wind and the measured active power at the grid terminals are equal both at sub-synchronous and super-synchronous speed operation. In order to limit the energy capture above the rated value pitch control has been implemented to the system and Simulation results show that the controller maintains the extracted energy till the rated value of the wind turbine mechanical power output.

Here, the optimal tracking has been applied using a look-up table for a given generator speed which needs accurate position sensor. Using the same control technique, it is better to give the command current for the rotor circuit directly without position sensor. The developed model can be used to study grid faults and this can be extended for further work.

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APPENDIX A- LIST OF SYMBOLS

P is the derivative symbol

V_{ds}, V_{qs} are the three-Phase supply voltages in d-q reference frame, respectively

i_{ds}, i_{qs} are the three-Phase stator currents in d-q reference frame, respectively

$\lambda_{ds}, \lambda_{qs}$, the three-Phase stator flux linkages in d-q reference frame, respectively

V_{dr}, V_{qr} are the three-Phase rotor voltages in d-q reference frame, respectively

i_{dr}, i_{qr} are the three-Phase rotor currents in d-q reference frame, respectively

$\lambda_{dr}, \lambda_{qr}$ are the three-Phase rotor flux linkages in d-q reference frame respectively

V_g, i_g are the grid voltages and the grid-side converter currents, respectively

r_s, r_r are the stator and rotor resistances of machine per phase, respectively

L_{1s}, L_{1r} are the leakage inductances of stator and rotor windings, respectively

w_s, w_r are rotational speed of the magnetic flux in the air gap of the generator and rotational speed of the rotor, respectively

T_m is the mechanical torque applied to rotor.

T_{em} is the electromagnetic torque applied to the rotor by the generator

P_m is the mechanical power captured by the wind turbine, transmitted to the rotor

P_s, Q_s are the stator-side active and reactive powers, respectively

$P_{s,ref}, Q_{s,ref}$ are the reference values of the stator active and reactive power

P_{gc}, Q_{gc} are the grid converter active and reactive powers, respectively

P_r, Q_r are the rotor-side active and reactive powers, respectively

$Q_{r,ref}$ is the reference value of the reactive power flow between the grid and the grid-side converter

J, wind turbine moment of inertia

p is the Number of pole pairs

E is the DC-link voltage

E_{ref} is the reference value of the DC-link voltage and C is the dc link capacitance

APPENDIX B - MACHINE AND TURBINE PARAMETERS

$R_s = 0.00706$

$R_r = 0.005$

$L_{1s} = L_{1r} = 0.156$

$L_m = 2.9$

$V_{L-L} = 575V$

$P = 1.67Mw$

$p = 3$

$f = 50\,Hz$

$H = 5.04\,s$

$C = 0.01F$

Turbine specification

Nominal mechanical output power = 1.5MW

Base wind speed = 12 m/s

Maximum power at base wind speed = 0.73 p.u

Base rotational speed (p.u of the generator speed) = 1.2