RESEARCH ARTICLE OPEN ACCESS

# Wind Energy Using Doubly Fed Induction Generator

T.Divyapradeepa
*Neo Creative Vision Technology*

**ABSTRACT**
Wind energy, is the electrical energy obtained from harnessing the wind, Wind is a form of **solar energy**. They are caused by the uneven heating of the atmosphere by the sun, the irregularities of the earth's surface, and rotation of the earth. Wind flow patterns are modified by the earth's terrain, bodies of water, and vegetative cover. This wind flow, or motion energy, when "harvested" by modern **wind turbines**, can be used to generate **electricity**. it is an alternative to fossil fuels, available plentiful, and also a renewable, widely distributed, clean, and produces no greenhouse gas emissions during operation. The world has enormous resources of wind power. It has been estimated that even if 10% of raw wind potential could be put to use, all the electricity needs of the world would be met. A phased programme to develop wind energy in India started as early as 1985, and today the total installed capacity has reached 1650 MW, saving about 935,000 metric tonnes of coal. Wind electrical generation systems are the most cost-competitive of all the environmentally clean and safe renewable energy sources in the world. Traditionally, wind generation systems used variable pitch constant speed wind turbines (horizontal or vertical axis) that were coupled to squirrel cage induction generators or wound-field synchronous generators and fed power to utility grids or autonomous loads. The recent evolution of power semiconductors and variable frequency drives technology has aided the acceptance of variable speed generation systems. Such systems can yield 20-30% more power than constant-speed generation systems.

**Key Words:** wind power, renewable energy, generator, turbines,

Date of Submission: 12-12-2017 Date of acceptance: 28-12-2017

## I. INTRODUCTION

In recent years, wind energy has become one of the most economical renewable energy technology. Today, electricity generating wind turbines employ proven and tested technology, and provide a secure and sustainable energy supply. At good, windy sites, wind energy can already successfully compete with conventional energy production[1]. Many countries have considerable wind resources, which are still untapped.

A technology which offers remarkable advantages is not used to its full potential

- Wind energy produces no greenhouse gases.
- Wind power plants can make a significant contribution to the regional electricity supply and to power supply diversification.
- A very short lead time for planning and construction is required as compared to conventional power projects.
- Wind energy projects are flexible with regard to an increasing energy demand - single turbines can easily be added to an existing park.
- Finally, wind energy projects can make use of local resources in terms of labour, capital and materials.

**Fig 1**. Wind mill

The technological development of recent years, bringing more efficient and more reliable wind turbines, is making wind power more cost-effective. In general, the specific energy costs per annual kWh decrease with the size of the turbine notwithstanding existing supply difficulties.

Many African countries expect to see electricity demand expand rapidly in coming decades. At the same time, finite natural resources are becoming depleted, and the environmental impact of energy use and energy conversion has been generally accepted as a threat to our natural habitat. Indeed these have become major issues for international policy.[2]

Many developing countries and emerging economies have substantial unexploited wind energy potential. In many locations, generating electricity from wind energy offers a cost-effective alternative to thermal power stations. It has a lower impact on the environment and climate, reduces dependence on fossil fuel imports and increases security of energy supply[3].

For many years now, developing countries and emerging economies have been faced with the challenge of meeting additional energy needs for their social and economic development with obsolete energy supply structures. Overcoming supply bottlenecks through the use of fossil fuels in the form of coal, oil and gas increases dependency on volatile markets and eats into valuable foreign currency reserves. At the same time there is growing pressure on emerging newly industrialized countries in particular to make a contribution to combating climate change and limit their pollutant emissions.

In the scenario of alternatives, more and more developing countries and emerging economies are placing their faith in greater use of renewable energy and are formulating specific expansion targets for a ‘green energy mix’. Wind power, after having been tested for years in industrialized countries and achieving market maturity, has a prominent role to play here. In many locations excellent wind conditions promise inexpensive power generation when compared with costly imported energy sources such as diesel. Despite political will and considerable potential, however, market development in these countries has been relatively slow to take off. There is a shortage of qualified personnel to establish the foundations for the exploitation of wind energy and to develop projects on their own initiative. The absence of reliable data on wind potential combined with unattractive energy policy framework conditions deters experienced international investors, who instead focus their attention on the expanding markets in Western countries.

It is only in recent years that appreciable development of the market potential in developing countries and emerging economies has taken place. The share of global wind generating capacity accounted for by Africa, Asia and Latin America reached about 20% at the end of 2008, with an installed capacity of 26 GW. This is attributable above all to breathtaking growth in India and China: these two countries alone are responsible for 22 GW. This proves that economic use of wind energy in developing countries and emerging economies is possible, and also indicates that there is immense potential that is still unexploited [4].

The first commercial wind energy converters entered service back in the 1980s, although the wind energy boom as such did not begin until the mid 1990s, when the total installed wind generation capacity in the world was only 5,000 MW. Since then the installed capacity has increased at double-digit rates of annual growth. By the end of 2006 global installed capacity had reached 74,233 MW. Currently the industry is enjoying a boom with 239,000 MW installed globally as at 2011. Almost without exception, the installed systems are used to generate electricity. The largest market at present is still Europe, where some 48,545 MW (65%) is installed; of this, 22,000 MW is located in Germany (figures from end of 2006). Germany is also a leader among the system manufacturers. Four German companies are counted among the world’s major manufacturers, and the German component industry supplies gearboxes, clutches and other assemblies to numerous producers in other countries.

Even if it remains a matter of dispute whether wind energy would still be competitive without promotional support, it is beyond doubt that the wind industry has made considerable progress. While in the early 1990s the cost of systems still averaged almost 1,300 EUR/kW, in the meantime specific investment costs have fallen to around 900 EUR/kW. The advantages of mass production have been further boosted by considerable increases in the efficiency of turbines (greater hub height, larger rotor diameter etc.), which have improved the economics of wind energy. There are now turbines on the market with a rated output of up to 6 MW, for example. This trend further illustrates that the growth market in the wind industry is mainly seen in electricity generation and grid feed-in.[6]

### 1.1 The Technology

Wind power is the conversion of wind energy into electricity or mechanical energy using wind turbines. The power in the wind is extracted by allowing it to blow past moving blades that exert torque on a rotor. The amount of power transferred is dependent on the rotor size and the wind speed. Wind turbines range from small four hundred watt generators for residential use to several megawatt machines for wind farms and offshore. The small ones have direct drive generators, direct current output, aero elastic blades, lifetime bearings and use a vane to point into the wind; while the larger ones generally have geared power trains, alternating current output, flaps and are actively pointed into the wind.

Direct drive generators and aero elastic blades for large wind turbines are being researched and direct current generators are sometimes used. Since wind speed is not constant, the annual energy production of a wind converter is dependent on the capacity factor. A well sited wind generator will have a capacity factor of about 35%. This compares to typical capacity factors of 90% for nuclear plants, 70% for coal plants, and 30% for thermal plants.

As a general rule, wind generators are practical where the average wind speed is 4.5 m/s or greater. Usually sites are pre-selected on the basis of a wind atlas, and validated with on site wind measurements. Wind energy is plentiful, renewable, widely distributed, clean, and reduces greenhouse gas emissions if used to replace fossil-fuel-derived electricity. The intermittency of wind does not create problems when using wind power at low to moderate penetration levels[5].

### 1.2 Applications and Efficiency

Most modern wind power is generated in the form of electricity by converting the rotation of turbine blades into electrical current by means of an electrical generator. In windmills (a much older technology), wind energy is used to turn mechanical machinery to do physical work, such as crushing grain or pumping water [5]. Recently, wind energy has also been used to desalinate water.

### 1.3 Wind energy for Development

"The wind energy potential in many developing and emerging countries is substantial. In many locations, generating electricity from wind energy presents an economically viable alternative to the use of conventional fossil energy sources such as coal or diesel. In developing and emerging countries, wind turbines are an alternative to conventional power stations. In comparison to fossil-fueled power stations, wind energy can now be cost-effective in many places, as well as being non-polluting and reducing dependence on imports of fossil fuels."

Advantages of wind can be:

- Use of an indigenous resource without producing greenhouse gases or other pollution;
- Wind energy contributes to the power supply diversification,
- Wind energy projects can develop local resources in terms of labour, capital and materials,
- Wind projects reinforce the cooperation with different donors including Germany, enhacing local capacities and technological know-how,
- Wind projects attract new capital and can be included in the new approach of Independent Power Production (IPP).[7]

### Challenges:

Despite the economic and ecological advantages, so far even good wind resources in developing and emerging countries have not been used to the desirable extent.

The essential reasons for this are based in the lack of knowledge in the developing and emerging countries.

From the view of international wind energy companies, beside the difficulties of raising of capital and risk covering the barriers for private investment are especially:

- Lack of information on foreign markets
- Lack of knowledge of the energy-sector framework conditions and support mechanisms
- Insufficient wind energy legal framework
- Lack of qualified staff, especially in the field of service/maintenance [8]. Technicians and buyers are often unfamiliar with wind technology, and in remote locations installments often break down because of a lack of servicing, spare parts, or trained manpower to administer them. In reality, wind pumps are less maintenance intensive than diesel pumps. However, the wind pump technology is "strange" to many people and there is a need to train maintenance staff where pumps are installed.
- Infrastructure to support the installation, commissioning and maintenance of wind generators is not developed. Users and technicians are generally unaccustomed to the technology.
- Investment Cost. Although the lifetime cost of wind is often less than diesel or petrol-powered pumps, the investment cost of purchasing a wind pump is usually higher than that of diesel pumps. Groups purchasing water supplies often have limited funds and cannot take a long-term view toward the technology.
- Wind energy does not have as consistent an output as fuel-fired power plants. Small-scale wind generators require battery storage to allow usage in periods of low or no wind. For grid connected systems, a stable grid is required to act as the storage. Wind pumps require water storage.
- Wind generators are designed to work over a given range of wind speeds, usually 4– 12m/s. This means that the technology can only be used in areas with sufficient winds[5].
- The major challenge to using wind as a source of power is that it is **intermittent** and does not always blow when electricity is needed. Wind cannot be stored (although wind-generated electricity can be stored, if batteries are used), and not all winds can be harnessed to meet the timing of electricity demands. Further, good wind sites are often located in **remote locations** far from areas of electric power demand (such as cities). Finally, wind resource development may compete with other uses for the land, and those **alternative uses** may be more highly valued than electricity generation. However, wind turbines can be located on land that is also used for grazing or even farming.

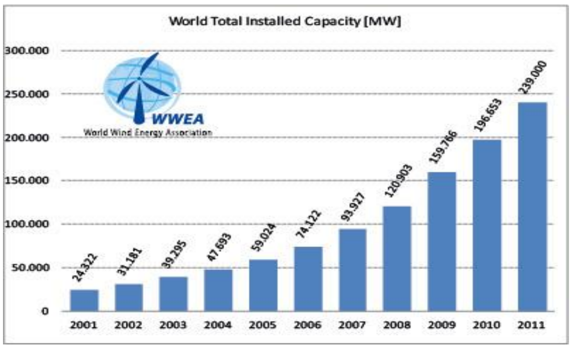

**Fig.2 Global installed Wind capacity**

## II. WIND ENERGY AND WIND POWER

Wind is a form of **solar energy**. Winds are caused by the uneven heating of the atmosphere by the sun, the irregularities of the earth's surface, and rotation of the earth. Wind flow patterns are modified by the earth's terrain, bodies of water, and vegetative cover. This wind flow, or motion energy, when "harvested" by modern **wind turbines**, can be used to generate **electricity**.

### *2.1 How Wind Power Is Generated*

The terms "**wind energy**" or "**wind power**" describe the process by which the wind is used to generate **mechanical power or electricity**. Wind turbines convert the kinetic energy in the wind into mechanical power. This mechanical power can be used for specific tasks (such as grinding grain or pumping water) or a generator can convert this mechanical power into electricity to power homes, businesses, schools, and the like.

### 1) Wind Turbines

**Wind turbines** convert the kinetic **energy** in the **wind** into mechanical **power.** This mechanical energy is then converted into electricity that is sent to a power grid. The mechanical **power** can be used for specific tasks (such as grinding grain or pumping water) or a generator can convert this mechanical **power** into electricity to **power** homes, businesses, schools, and the like. The turbine components responsible for these energy conversions are the rotor and the generator. The rotor is the area of the turbine that consists of both the turbine hub and blades. As wind strikes the turbine's blades, the hub rotates due to aerodynamic forces. This rotation is then sent through the transmission system to decrease the revolutions per minute. The transmission system consists of the main bearing, high-speed shaft, gearbox, and low-speed shaft. The ratio of the gearbox determines the rotation division and the rotation speed that the generator sees. For example, if the ratio of the gearbox is N to 1, then the generator sees the rotor speed divided by N. This rotation is finally sent to the generator for mechanical-to-electrical conversion. Figure 1 shows the major components of a wind turbine: gearbox, generator, hub, rotor, low-speed shaft, high-speed shaft, and the main bearing. The purpose of the hub is to connect the blades' servos that adjust the blade direction to the low-speed shaft. The rotor is the area of the turbine that consists of both the hub and blades. The components are all housed together in a structure called the nacelle.

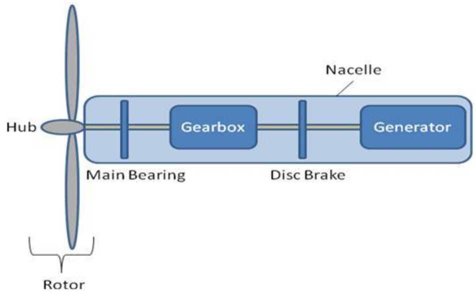

**Figure 3 .** The Major Components of a Wind Turbine

### Angle of Attack

The amount of surface area available for the incoming wind is key to increasing aerodynamic forces on the rotor blades. The angle at which the blade is adjusted is referred to as the angle of attack, α. This angle is measured with respect to the incoming wind direction and the chord line of the blade. There is also a critical angle of attack, $\alpha_{critical}$, where air no longer streams smoothly over the blade's upper surface. Figure 2 shows the critical angle of attack with respect to the blade.

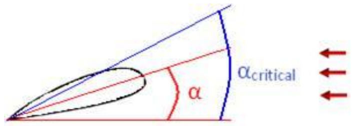

**Fig 2.** The Critical Angle of Attack ($\alpha_{critical}$) with Respect to the Blade

### Power and Efficiency

This section explains what affects the power extracted from the wind and the efficiency of this process. Consider Figure 3 as a model of the turbine's interaction with the wind. This diagram indicates that wind exists on either side of the turbine, and the proper balance between rotational speed and the velocity of wind are critical to regulate performance.

$$\gamma = \frac{2\pi f r}{v1} \qquad (1)$$

f-frequency of blade rotation
r-length of the blade
Equ 1- Calculating the Tip Speed ratio

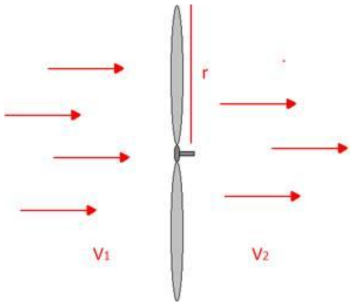

**Fig 3.** Model of the Turbine's Interaction with the Wind

The efficiency of a wind turbine is called the power coefficient, or $C_p$. Theoretically, the power coefficient is calculated as the ratio of actual to ideal extracted power. You can find this calculation in Equation 2. Also, you can adjust $C_p$ by controlling the angle of attack, α, and the tip speed ratio, $\lambda$. The calculation for this case is shown in Equation 3. In Equation 3, c1-c6 and x are coefficients that wind turbine manufacturer should provide. Note that the maximum power coefficient that you can achieve with any turbine is .59, or the Betz limit.

$$Cp = \frac{Pactual}{Pideal}$$

$$= \frac{25\rho A(v1^2 - v2^2)(v1+v2)}{(0.5\rho A v1^3)} \qquad (2)$$

**The power coefficient is calculated as the ratio of actual to ideal extracted power.**

$$Cp(\gamma, \alpha) = c1\left(c2\left(\frac{1}{\beth}\right) - c3\alpha - c4\alpha^x - c5e{-}c61\beth\right.(3)$$

$$\frac{1}{\beth} = \frac{1}{\gamma + 0.08\alpha} - \left(\frac{0.35}{1+\alpha^3}\right)$$

Equation 3.You can adjust the by controlling the angle of attack, α, and the tip speed ratio.

Finally, you can calculate the usable power from the wind using Equation 5. From this equation, you can see that the main drivers for usable power are the blade length and wind speed.

$$P = \frac{Cp(\gamma,\alpha)\rho\pi r^2 v1^3}{2} \quad (4)$$

$$\rho = density\ of\ air\left(\frac{1.2929kg}{m3}\right)$$

Equation 4 is for calculating usable power from the wind

### The Power Curve

It is important to understand the relationship between power and wind speed to determine the required control type, optimization, or limitation. The power curve, a plot you can use for this purpose, specifies how much power you can extract from the incoming wind. Figure 4 contains an ideal wind turbine power curve.

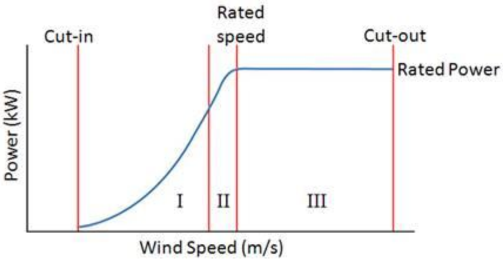

**Fig 4.** Ideal Wind Turbine Power Curve

The cut-in and cut-out speeds are the operating limits of the turbine. By staying in this range, you ensure that the available energy is above the minimum threshold and structural health is maintained. The rated power, a point provided by the manufacturer, takes both energy and cost into consideration. Also, the rated wind speed is chosen because speeds above this point are rare. Typically, you can assume that a turbine design that extracts the bulk of energy above the rated wind speed is not cost-effective.

From Figure 4, you can see that the power curve is split into three distinct regions. Because Region I consists of low wind speeds and is below the rated turbine power, the turbine is run at the maximum efficiency to extract all power. In other words, the turbine controls with optimization in mind. On the other hand, Region III consists of high wind speeds and is at the rated turbine power. The turbine then controls with limitation of the generated power in mind when operating in this region. Finally, Region II is a transition region mainly concerned with keeping rotor torque and noise low.

### Control Methods

You can use different control methods to either optimize or limit power output. You can control a turbine by controlling the generator speed, blade angle adjustment, and rotation of the entire wind turbine. Blade angle adjustment and turbine rotation are also known as pitch and yaw control, respectively. A visual representation of pitch and yaw adjustment is shown in Figures 5 and 6.

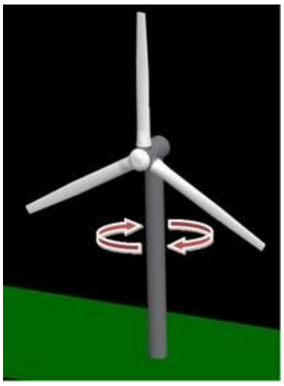

Fig.5 Pitch adjustment

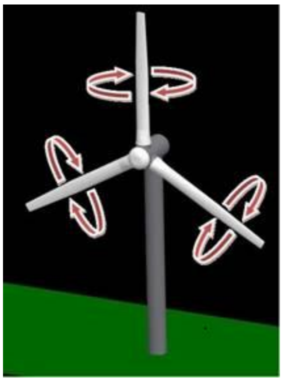

Fig.6 Yaw adjustment

The purpose of pitch control is to maintain the optimum blade angle to achieve certain rotor speeds or power output. You can use pitch adjustment to stall and furl, two methods of pitch control. By stalling a wind turbine, you increase the angle of attack, which causes the flat side of the blade to face further into the wind. Furling decreases the angle of attack, causing the edge of the blade to face the oncoming wind. Pitch angle adjustment is the most effective way to limit output power by changing aerodynamic force on the blade at high wind speeds.

Yaw refers to the rotation of the entire wind turbine in the horizontal axis. Yaw control ensures that the turbine is constantly facing into the wind to maximize the effective rotor area and, as a result, power. Because wind direction can vary quickly, the turbine may misalign with the oncoming wind and cause power output losses. You can approximate these losses with the following equation:

$\Delta P = \alpha \cos(\varepsilon)$ (5)

Where $\Delta P$ is the lost power and $\varepsilon$ is the yaw error angle

The final type of control deals with the electrical subsystem. You can achieve this dynamic control with power electronics, or, more specifically, electronic converters that are coupled to the generator. The two types of generator control are stator and rotor. The stator and rotor are the stationary and non stationary parts of a generator, respectively. In each case, you disconnect the stator or rotor from the grid to change the synchronous speed of the generator independently of the voltage or frequency of the grid. Controlling the synchronous generator speed is the most effective way to optimize maximum power output at low wind speeds.

Figure 7 shows a system-level layout of a wind energy conversion system and the signals used. Notice that control is most effective by adjusting pitch angle and controlling the synchronous speed of the generator.

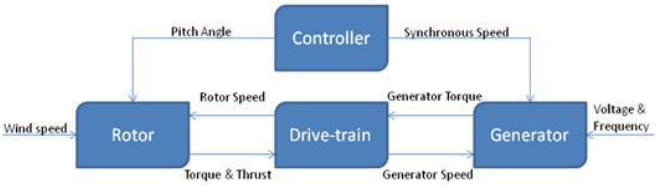

**Fig 7.** System-Level Layout of a Wind Energy System

**Control Strategies**

Recall that controlling the pitch of the blade and speed of the generator are the most effective methods to adjust output power. The following control strategies use pitch and generator speed control to manage turbine functionality throughout the power curve: fixed-speed fixed-pitch, fixed-speed variable-pitch, variable-speed fixed-pitch, and variable-speed variable-pitch. Figure 8 shows the power curves for different control strategies explained below, with variable-speed variable-pitch, VS-VP, being the ideal curve.

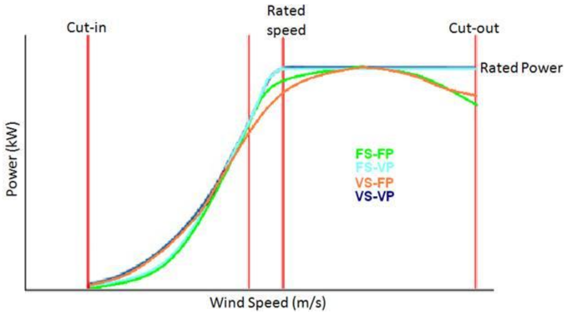

**Figure 8.** Power Curves for Different Control Strategies (Variable-speed variable-pitch, VS-VP, is the ideal curve.)

**Fixed-speed fixed-pitch** (FS-FP) is the one configuration where it is impossible to improve performance with active control. In this design, the turbine's generator is directly coupled to the power grid, causing the generator speed to lock to the power line frequency and fix the rotational speed. These turbines are regulated using passive stall methods at high wind speeds. The gearbox ratio selection becomes important for this passive control because it ensures that the rated power is not exceeded. Figure 8 shows the power curve for FS-FP operation.

From the figure, it is apparent that the actual power does not match the ideal power, implying that there is lower energy capture. Notice that the turbine operates at maximum efficiency only at one wind speed in the low-speed region. The rated power of the turbine is achieved only at one wind speed as well. This implies poor power regulation as a result of constrained operations.

**Fixed-speed variable-pitch** (FS-VP) configuration operates at a fixed pitch angle below the rated wind speed and continuously adjusts the angle above the rated wind speed. To clarify, fixed-speed operation implies a maximum output power at one wind speed. You can use both feather and stall pitch control methods in this configuration to limit power. Keep in mind that feathering takes a significant amount of control design and stalling increases unwanted thrust force as stall increases. Figure 8 shows the power curve for FS-VP using either feather or stall control.

Below the rated wind speed, the FS-VP turbine has a near optimum efficiency around Region II. Exceeding the rated wind speed, the pitch angles are continuously changed, providing little to no loss in power.

**Variable-speed fixed-pitch** (VS-FP) configuration continuously adjusts the rotor speed relative to the wind speed through power electronics controlling the synchronous speed of the generator. This type of control assumes that the generator is from the grid so that the generator's rotor and drive-train are free to rotate independently of grid frequency. Fixed-pitch relies heavily on the blade design to limit power through passive stalling. Figure 8 shows the power curve for VS-FP.

Figure 8 shows that power efficiency is maximized at low wind speeds, and you can achieve rated turbine power only at one wind speed. Passive stall regulation plays a major role in not achieving the rated power and can be attributed to poor power regulation above the rated wind speed. In lower wind speed cases, VS-FP can capture more energy and improve power quality.

**Variable-speed variable-pitch** (VS-VP) configuration is a derivation of VS-FP and FS-VP. Operating below the rated wind speed, variable speed and fixed pitch are used to maximize energy capture and increase power quality. Operating above the rated wind speed, fixed speed and variable pitch permit efficient power regulation at the rated power. VS-VP is the only control strategy that theoretically achieves the ideal power curve shown in Figure 8.

Wind turbines, like aircraft propeller blades, turn in the moving air and power an **electric generator** that supplies an electric current. Simply stated, a wind turbine is the opposite of a fan. Instead of using electricity to make wind, like a fan, wind turbines use wind to make electricity. The wind turns the blades, which spin a shaft, which connects to a generator and makes electricity.

Wind energy is not a constant source of energy. It varies continuously and gives energy in sudden bursts. About 50% of the entire energy is given out in just 15% of the operating time. Wind strengths vary and thus cannot guarantee continuous power. It is best used in the context of a system that has significant reserve capacity such as hydro, or reserve load, such as a desalination plant, to mitigate the economic effects of resource variability.

**Betz Limit:**

No wind turbine could convert more than **59.3%** of the kinetic energy of the wind into Mechanical energy turning a rotor. This is known as the Betz Limit, and is the theoretical Maximum coefficient of power for any wind turbine. The maximum value of $\mathbf{C_p}$ according to Betz limit is 59.3%. For good turbines it is in the range of 35-45%.

**Types of Wind energy Conversion Devices.**

A wind turbine is a rotating machine which converts the kinetic energy in wind into mechanical energy. If the mechanical energy is then converted to electricity, the machine is called a wind generator, wind turbine, wind power unit (WPU), wind energy converter (W EC), or aero generator.

Wind turbines can be separated into two types based by the axis in which the turbine rotates. Turbines that rotate around a horizontal axis are more common. Vertical-axis turbines are less frequently used.

The total capacity of wind power on this earth that can be harnessed is about 72 TW. There are now many thousands of wind turbines operating in various parts of the world, with utility companies having a total capacity of 59,322 MW. The power generation by wind energy was about 94.1GW in 2007 which makes up nearly 1% of the total power generated in the world. Globally, the long-term technical potential of wind energy is believed to be 5 times current global energy consumption or 40 times current electricity demand. This would require covering 12.7% of all land area with wind turbines. This land would have to be covered with 6 large wind turbines per square kilometre

The power extracted from the wind can be calculated by the given formula:

$$Pw = 0.5\rho\pi r^2 v1^3 Cp(\gamma,\alpha) \quad (6)$$

***Wind Turbine Types***

Modern wind turbines fall into two basic groups; the **horizontal-axis** variety, like the traditional farm windmills used for pumping water, and the **vertical-axis** design. Most large modern wind turbines are horizontal-axis turbines. as shown in the photo to the far right, and the vertical-axis design, like the eggbeater-style Darrieus model pictured to the immediate right, named after its French inventor. Horizontal-axis wind turbines typically either have two or three blades. These three-bladed wind turbines are operated "upwind," with the blades facing into the wind.

**Fig 9.** Horizontal axis and Vertical axis

Wind turbines can be built on land or offshore in large bodies of water like oceans and lakes. The U.S. Department of Energy is funding efforts that will make innovative offshore wind technology available in U.S. waters.

### *Turbine Components*

Horizontal turbine components include:

- **blade** or **rotor**, which converts the energy in the wind to rotational shaft energy;
- a **drive train**, usually including a gearbox and a generator;
- a **tower** that supports the rotor and drive train; and
- other equipment, including controls, electrical cables, ground support equipment, and interconnection equipment.

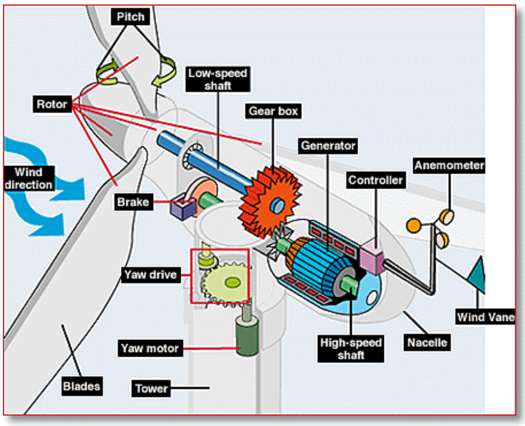

**Fig. 10 Wind turbine components**

### *Turbine Configurations*

Wind turbines are often grouped together into a single wind power plant, also known as a **wind farm**, and generate bulk electrical power. Electricity from these turbines is fed into a utility grid and distributed to customers, just as with conventional power plants.

### *Wind Turbine Size and Power Ratings*

Wind turbines are available in a variety of sizes, and therefore power ratings. The largest machine has blades that span more than the length of a football field, stands 20 building stories high, and produces enough electricity to power 1,400 homes. A small home-sized wind machine has rotors between 8 and 25 feet in diameter and stands upwards of 30 feet and can supply the power needs of an all-electric home or small business. **Utility-scale turbines** range in size from 50 to 750 kilowatts. Single small turbines, below 50 kilowatts, are used for homes, telecommunications dishes, or water pumping.

### *How wind Turbine works*

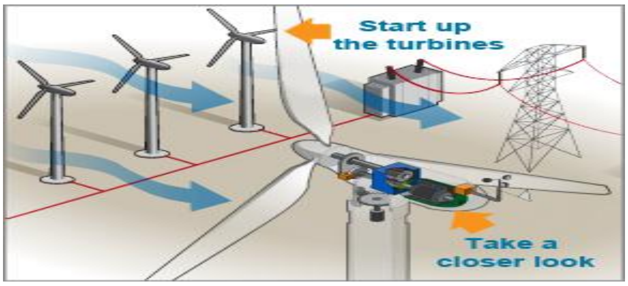

**Fig.11** How wind turbine works

Wind turbines operate on a simple principle. The energy in the wind turns two or three propeller-like blades around a rotor. The rotor is connected to the main shaft, which spins a generator to create electricity. a wind turbine works the opposite of a fan. Instead of using electricity to make wind, like a fan, wind turbines use wind to make electricity. The wind turns the blades, which spin a shaft, which connects to a generator and makes electricity. Wind is a form of solar energy and is a result of the uneven heating of the atmosphere by the sun, the irregularities of the earth's surface, and the rotation of the earth. Wind flow patterns and speeds vary greatly across the United States and are modified by bodies of water, vegetation, and differences in terrain. Humans use this wind flow, or motion energy, for many purposes: sailing, flying a kite, and even generating electricity.

The terms wind energy or wind power describe the process by which the wind is used to generate mechanical power or electricity. Wind turbines convert the kinetic energy in the wind into mechanical power. This mechanical power can be used for specific tasks (such as grinding grain or pumping water) or a generator can convert this mechanical power into electricity. Wind turbine capacity factor Due to the intermittent nature of wind, wind turbines do not make power all the time. Thus, a capacity factor of a wind turbine is used to provide a measure of the wind turbine’s actual power output in a given period (e.g. a year) divided by its power output if the turbine has operated the entire time. A reasonable capacity factor would be 0.25–0.30 and a very good capacity factor would be around 0.40 [ 50 ]. In fact, wind turbine capacity factor is very sensitive to the average wind speed.

**Solidity:** The solidity of a wind rotor is the ratio of the projected blade area to the area of the wind intercepted. The projected blade area is the blade area met by the wind or projected in the direction of the wind. Solidity has a direct connection with the torque and speed. High-solidity rotors have high torque and low speed, and are employed for pumping water. Low-solidity rotors, on the other hand, have high speed and low-torque, and are usually suited for electrical power generation

***TIP SPEED RATIO*:**

Tip speed ratio of a wind turbine (λ) is defined as:

$$\gamma = \frac{2\pi rN}{V\infty} \qquad (7)$$

Where ω is rotational speed of rotor (in rpm), r is the radius of the swept area (in meter).The tip speed ratio $\gamma$ and the power coefficient $C_p$ are the dimensionless and so can be used to describe the performance of any size of wind turbine rotor.

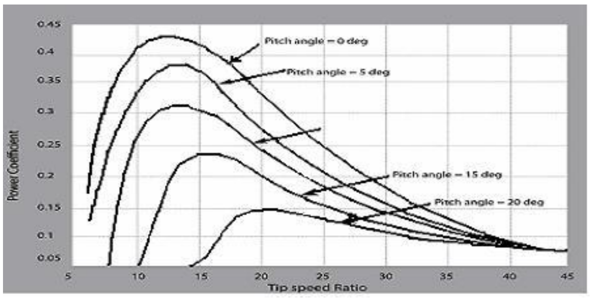

**Fig 12. Power Coefficient vs. tip speed ratio for various values of pitch angle**

***SPECIFIED RATED CAPACITY:***

Specified Rated capacity (SRC) is an important index which is used to compare a variety of wind turbine designs.

It varies between 0.2 (for small rotors) and 0.6 (large rotors)

***PRINCIPLE OF CONTROL***

***Aerodynamic Power Control for Wind Turbines***

When a generator reaches rated power, the turbines must limit the mechanical power delivered to the generator. This is valid because the generator reaches the rated power at for instance 15 m/s while the maximum speed is typically 25 m/s for a wind turbine. Control is done by three different methods called stall, pitch and a combination called active stall.

There are no moving parts in the stall-controlled blades and the challenge is in the construction of the blades to avoid vibration and make them stall gradually.

The pitch angle is controlled to keep the generator power at rated power by reducing the angle of the blades. By regulating, the angle to be on the of stalling, fast torque changes from the wind will be reutilized (Nayar and Bundell 1987).

The power captured by the turbine is given by

$$P_m = P_w \times C_p \qquad (8)$$

***CHARACTERISTICS OF WIND TURBINE*:**

Various Characteristics of wind turbine are plotted to have a better understanding.

***POWER-SPEED CHARACTERISTICS*:**

Mechanical Power transmitted to the shaft is:

$$\text{Pm}=0.5\rho CpAV\infty^3 \qquad (9)$$

Where

Cp is a function of tip speed ratio (TSR) and pitch angle α

For wind turbine with radius

The following curves show the relationship between mechanical power extracted from the wind and the rotor speed at various wind speeds. For each wind speed there is an optimum turbine speed at which maximum power is extracted.

Such a group of wind turbine characteristic curve, explicitly, the Cp-$\gamma$ curve such a group of wind turbine curves can be represented by a single dimensionless curve as shown in figure2.2

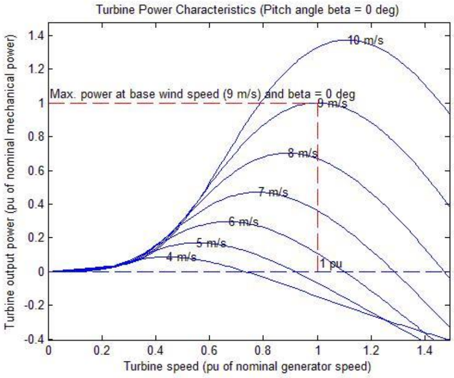

**Fig: 13** Typical Power versus speed characteristics of a wind turbine

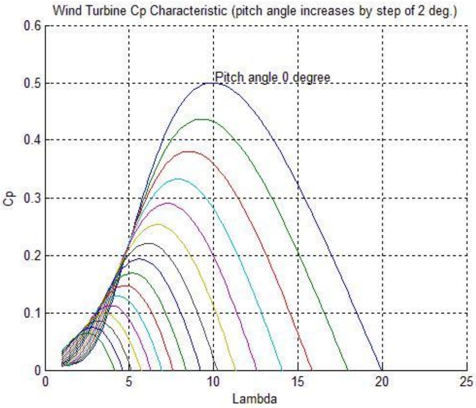

**Fig: 14** Typical curves of power coefficient (Cp) Versus Tip speed ratio ($\gamma$ )for various angles of pitch angle.

## III. TORQUE –SPEED CHARACTERISTICS:

The typical torque versus speed characteristics of horizontal axis (two blade propeller type) wind turbine is shown:

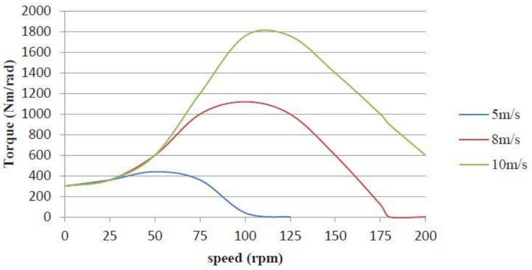

**Fig 15:** Torque and speed characteristics

The direct relationship between Torque and Power is

$$Tm = \frac{Pm}{\omega}$$

Equation 10

Using the optimum values of Cp and $\gamma$, the maximum value of aerodynamic torque is:

$$Tmax = 0.5\rho Cp - opt\pi\left(\frac{r^5}{\gamma opt^3}\right)\omega^2$$

Equation 11

The curve shows that for any wind speed the torque reaches peak value at a definite rotational speed, and this maximum torque varies in the order of the square of rotational speed. Generally the load torque depends on the electrical loading. The torque can be made to vary as the square of the rotational speed by choosing the load properly. Different control techniques such as Pitch angle control, Stall control (active and passive), Power electronic control and Yaw control are used to control the wind turbines.

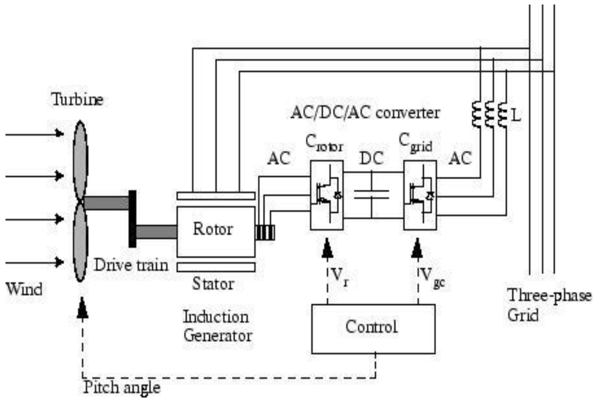

**Fig 16 :** A DFIG and wind turbine system

## IV. DOUBLY FED INDUCTION GENERATOR

Currently DFIG wind turbines are increasingly used in large wind farms. A typical DFIG system is shown in the below figure. The AC/DC/AC converter consists of two components: the rotor side converter $C_{rotor}$ and Grid side converter $C_{grid}$ .These converters are voltage source converters that use forced commutation power electronic devices (IGBTS) to synthesize AC voltage from DC voltage source. A capacitor connected on DC side acts as a DC voltage source. The generator slip rings are connected to the rotor side converter, which shares a DC link with the grid side converter in a so called back -to-back configuration. The wind power captured by the turbine is converted into electric power by the IG and is transferred to grid by stator and rotor windings. The control system gives the pitch angle command and the voltage commands for $C_{rotor}$ and $C_{grid}$ to control the power of the wind turbine, DC bus voltage and reactive power or voltage at grid terminals.

***OPERATION:***

When the rotor speed is greater than the rotating magnetic field from stator, the stator induces a strong current in the rotor. The faster the rotor rotates, the more power will be transferred as an electromagnetic force to the stator, and in turn converted to electricity which is fed to the electric grid. The speed of asynchronous generator will vary with the rotational force applied to it. Its difference from synchronous speed in percent is called generator‘s slip. With rotor winding short circuited, the generator at full load is only a few percent. With the DFIG, slip control is provided by the rotor and grid side converters. At high rotor speeds, the slip power is recovered and delivered to the grid, resulting in high overall system efficiency. If the rotor speed range is limited, the ratings of the frequency converters will be small compared with the generator rating, which helps in reducing converter losses and the system cost. Since the mechanical torque applied to the rotor is positive for power generation and since the rotational speed of the magnetic flux in the air gap of the generator is positive and constant for a constant frequency grid voltage, the sign of the rotor electric power output is a function of the slip sign. $C_{rotor}$ and $C_{grid}$ have the capability of generating or absorbing reactive power and can be used for controlling the reactive power or the grid terminal voltage. The pitch angle is controlled to limit the generator output power to its normal value for high wind speeds. The grid provides the necessary reactive power to the generator.

### *4.1 Steady state characteristics*:

The steady state performance can be explained using Steinmetz per phase equivalent circuit model as shown in figure where motor convention is used. In this figure $v_s$ and $v_r$ are the stator and rotor voltages, $i_s$ and $i_r$ are the stator and rotor currents, $r_s$ and $r_r$ are the stator and rotor resistances (per phase), $X_s$ and $X_r$ are stator and rotor leakage reactance‘s, $X_m$ is the magnetizing reactance and $s$ is slip.The steady state equivalent circuit of DFIG is shown in Fig.17

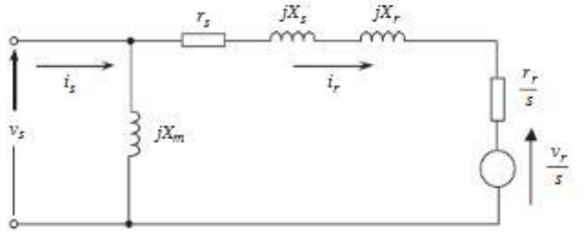

**Fig: 17** steady state equivalent circuit of DFIG

To obtain the torque equation from the equivalent circuit, we can simplify the steady state induction motor circuit by moving $X_m$ to the stator terminal .The rotor current $I_r$ is expressed as

$$Ir = \frac{Vs - \frac{Vr}{s}}{\left(rs + \frac{rr}{s}\right) + j(Xs + Xr)}$$

Equation 13

The electrical torque $T_e$, from the power balance across the stator to rotor gap, can be calculated from

$Te = \frac{Ir^2 rr}{s} + Pr/s$ Equation 14

Where the power supplied or absorbed by the controllable source injecting voltage into the rotor circuit, that is the rotor active power, $P_r$ can be calculated from

$Pr = \frac{VrIr}{s} Cos\theta$ Equation 15

$Pr = Re(\left(\frac{Vr}{s}\right) Ir *$ Equation 16

### *TORQUE-SLIP CHARACTERISTICS OF DFIG*:

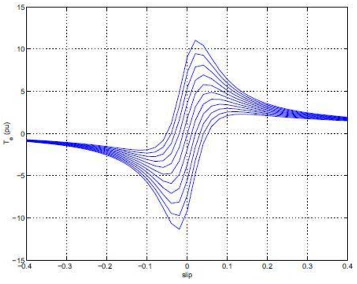

**Fig: 18** Torque-slip characteristic when the angle of Vr is 0. |Vr| is changing from -0.05 to +0.05 pu.

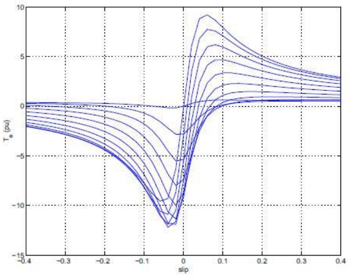

**Fig: 19** Torque-slip characteristic when |Vr| is 0.05 pu. The angle of Vr is changing from −90◦ to +90◦.

### *4.2 CONTROL STRATEGIES FOR A DFIG*:

1. Vector control
2. Magnitude and frequency control

### *4.2.1 VECTOR OR FIELD ORIENTED CONTROL THEORY*:

The complete control strategy of the machine is divided in two ways, one is scalar control and the other is vector control. The limitations of scalar control give a significance to vector control. Though the scalar control strategy is modest to implement but the natural coupling effect gives sluggish response. The inherent problem is being solved by the vector control. The vector control is invented in the beginning of 1970s. Using this control strategy an IM can be performed like dc machine. Because of dc machine like performance vector control is also known as orthogonal, decoupling or Tran‘s vector control. Different Vector control strategies have been proposed to control the active and reactive power of an induction generator.

The basic of the vector control theory is d-q theory. To understand vector control theory knowledge about d-q theory is essential.

### *D-Q THEORY*:

The d-q theory is also known as reference frame theory. The history says in 1920, R. H. Park suggested a new theory to overcome the problem of time varying parameters with the ac machines. He formulated a change of variables which replace the variables related to the stator windings of a synchronous machine with variables related with fictitious winding which rotates with the rotor at synchronous speed.

Essentially the transformed the stator variables to a synchronously rotating reference frame fixed in the rotor. With such transformation (Park‘s transformation) he showed that all the time varying inductances that occur due to an electric circuit in relative motion and electric circuit with varying magnetic reluctances can be eliminated. Later in 1930s H. C. Stanley showed that time varying parameters can be eliminated by transforming the rotor variables to the variables associated with fi In this case the rotor variables are transformed to the stationary reference frame fixed on the stator. Later G. Kron proposed transformation of stator and rotor variables to a synchronously rotating reference frame which moves with rotating magnetic field. Latter, Krause and Thomas had shown that the time varying Inductances can be eliminated by referring the stator and rotor variables to an arbitrary reference frame which may rotate at any speed [5].

### *TRANSFORMATION OF THREE PHASE STATIONARY TO TWO PHASE STATIONARY AXES:*

Consider a symmetrical three phase induction machine with stationary a-phase, b phase and c-phase axes are placed at 120° angle to each other as shown in Fig 4.5. The main aim is to transform the three phase stationary frame variables into two phase stationary frame variables ($d^s$-$q^s$) and then transform these to synchronously rotating reference frame variables (d-q), and vice versa.

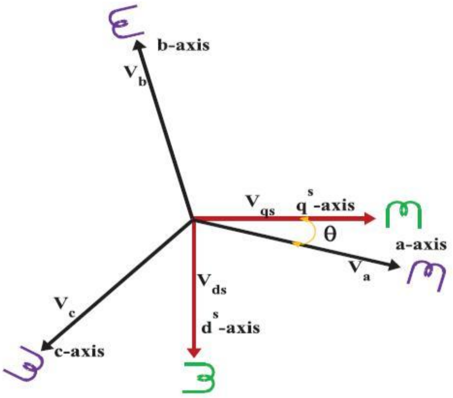

**Fig 20:** Transformation of a-b-c to $d^s$-$q^s$ axes

Let $d^s$-$q^s$ axes are oriented at an angle from a-b-c axes as shown in Fig 4.2 The voltage ($V_{ds}{}^s$ and $V_{qs}{}^s$) can be resolved into a-b-c components and can be represented in the matrix form as

$$\begin{array}{lccc} va & cos\theta & sin\theta & 1\ Vqs^2 \\ vb = \{ & \cos(\theta - 120) & \sin(\theta - 120) & 1\}Vds^2 \\ vc & \cos(\theta + 120) & \sin(\theta + 120) & 1\ Vos^2 \end{array}$$

(17)

The corresponding inverse relation as

$$\begin{bmatrix} Vqs^2 \\ Vds^2 \\ Vos^2 \end{bmatrix} = \begin{bmatrix} cos\theta & \cos(\theta - 120) & \cos(\theta + 120) \\ sin\theta & \sin(\theta - 120) & \sin(\theta + 120) \\ 0.5 & 0.5 & 0.5 \end{bmatrix} \begin{matrix} va \\ [vb] \\ vc \end{matrix} \quad (18)$$

Where $Vos^2$ is added as the zero sequence component. Other parameters like current, flux linkages can be transformed by similar manner. It is more convenient to set θ=0°, so that q-axis is aligned with the a-axis in this case (The alignment of the axes are optional, d-axis can also be aligned with a-axis). The sine components of d and q parameters will be replaced with cosine values, and vice versa if d-axis coincides with a-axis.

### *Transformation of two phase stationary axes to two phase synchronously rotating axes*:

Fig 21 below shows the synchronously rotating d-q axes which rotate at synchronous speed $\square_e$ with respect to $d^s$-$q^s$ axes. The two phase windings are transformed in to the fictitious windings mounted on the d-q axes.

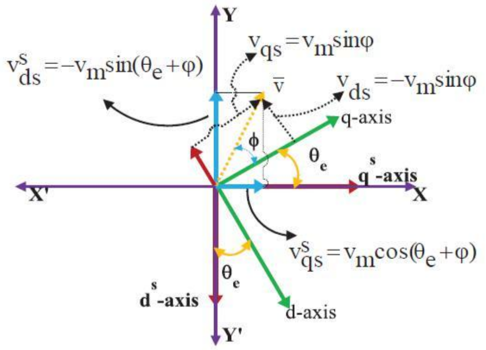

**Fig.21** Transformation of stationary $d^s$-$q^s$ axes to synchronously rotating frame d-q axes

The voltages on the $d^s$-$q^s$ axes can be converted into d-q axes as follows;

$Vqs = V^s qsCos\theta e - V^s dsSin\theta e$ (19)

$Vds = V^s qsSin\theta e - V^s dsCos\theta e$(20)

Again resolving the rotating frame parameters into a stationary frame the relations are

$V^s qs = VqsCos\theta e - VdsSin\theta e$(21)

$V^s ds = -VqsSin\theta e + VdsCos\theta e$(22)

### *Mathematical modelling of Induction Generator:*

In this section the basic mathematical modelling of DFIG is described in detail. From the previous section we confirm that the three phase parameters can be represented in two phase parameters and vice versa using certain fundamental rules. In this section the machine modelling is explained by taking two phase parameters into consideration. Though the basic concepts behind the DFIG system is explained briefly in short we can say the DFIG is a wound rotor type induction machine, its stator consists of stator frame, stator core, poly phase (3-phase) distributed winding, two end covers, bearing etc. The stator core is made up of stack of cylindrical steel laminations which are slotted along their inner periphery for covering the 3-phase winding. Its rotor consists of slots in the outer periphery to house the windings like stator. The machine works on the principle of Electromagnetic Induction and the energy transfer takes place by means of transfer action. So the machine can represent as a transformer but rotatory not stationary.

***Modelling of DFIG in synchronously rotating frame:***

The equivalent circuit diagram of an induction machine is shown in Fig.4.7 and Fig.4.8. In this figure the machine is represented as two phase machine, it has already been discussed before that a three phase machine can be represented as two phase machine obeying certain rules. For the modelling of DFIG in synchronously rotating frame we need to represent the two phase stator ($d^s$-$q^s$) and rotor ($d^r$-$q^r$) circuit variables in a synchronously rotating (d-q) frame.

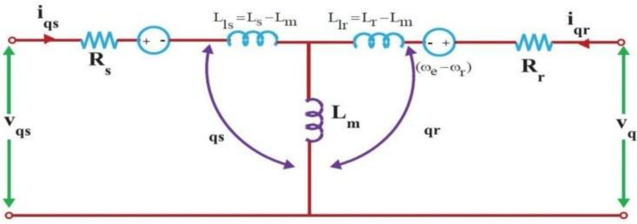

**Fig.22** Dynamic d-q equivalent circuit of DFIG (q-axis circuit)

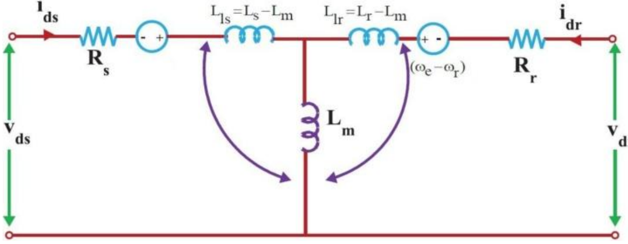

**Fig.23** Dynamic d-q equivalent circuit of DFIG (d-axis circuit)

The stator circuit equations are given below:

$$V^s qs = Rsi^s qs + d/dt\aleph^s qs \quad (23)$$

$$V^s ds = Rsi^s ds + d/dt\aleph^s ds \quad (24)$$

Where $\aleph^s qs$ and $\aleph^s ds$ are q-axis and d-axis stator flux linkages, respectively. Converting Eq. (4.7) and Eq. (4.8) to d-q frame the following equations can be written as:

$$Vqs = Rsiqs + \frac{d}{dt}\aleph qs + \omega e\aleph^s ds$$
(25)

$$Vds = Rsids + \frac{d}{dt}\aleph ds + \omega e\aleph^s qs$$
(26)

Where all the variables are in synchronously rotating frame. The bracketed terms are defined as the back e.m.f. or speed e.m.f or counter e.m.f. due to the rotation of axes as in the case of DC machines. When the angular speed □$_e$ is zero the speed e.m.f due to d and q axis is zero and the equations changes to stationary form.

Owing to the rotor circuit, if the rotor is blocked or not moving, the machine equations can be written in similar way as stator equations:

$$Vqr = Rriqr + \frac{d}{dt}\aleph qr + \omega e\aleph^s dr$$
(27)

$$Vdr = Rriqr + \frac{d}{dt}\aleph qr - \omega e\aleph^s dr$$
(28)

All the parameters are referred to the primary circuit, which is a stator in this case. Let the rotor rotates at an angular speed ωr , then the d-q axes fixed on the rotor fictitiously will move at a relative speed ωe-ωr to the synchronously rotating frame.

The d-q frame rotor equations can be written by replacing ωe-ωr in place ωe of as follows:

$$Vqr = RrIqr + \frac{d}{dt}\aleph qr + (\omega e - \omega r)\aleph dr$$
(29)

$$Vdr = RrIdr + \frac{d}{dt}\aleph dr - (\omega e - \omega r)\aleph qr$$
(30)

The flux linkage expressions in terms of current can be written from Fig.4.7 and Fig.4.8 as follows:

$$\aleph qs = L1siqs + Lm(iqs + iqr) = Lsiqs + Lmiqr$$
(31)

$$\aleph ds = L1sids + Lm(ids + idr) = Lsids + Lmidr$$
(32)

$$\aleph qr = L1riqr + Lm(iqs + iqr) = Lsiqr + Lmiqs$$
(33)

$$\aleph ds = L1sids + Lm(ids + idr) = Lsids + Lmidr$$
(34)

$$\aleph qm = Lm(iqs + iqr)$$
(35)

$$\aleph dm = Lm(ids + idr)$$
(36)

Eq. (4.21) expresses the relations of mechanical parameters which are essential part of the modelling.

$$Te = TL + \frac{Jd\omega m}{dt} + B\omega m$$
$$= TL + \frac{2}{p}J\, d\omega m/dt + 2/pB\omega r$$

(37)

The electrical speed $\omega_r$ cannot be treated as constant in the above equations. It can be connected to the torque as

***PRINCIPLE OF VECTOR CONTROL:***

The fundamentals of implementation of vector control technique can be explained using the Fig 4.9 In this figure the machine model is in synchronously rotating frame. The vector control uses unit vectors to obtain the appropriate control action. The main role of unit vector is to convert the 2-phase model to 3-phase model and vice versa. Though the control techniques used for DFIG uses two axes parameters as explained in the modelling via vector control but the model is virtual representation of the original machine. The control signals which will be fed to the original machine or converters should be in three axes form, so the process requires repeated conversion of two-phase to three-phase parameter or vice versa following the necessary action being taken for the system [6].

There are essentially two general method of vector control

1. Direct or feedback method (which is invented by Blaschke )
2. Indirect or feed forward method ( which is invented by Hasse)

The two methods are different from each other by the process of generating unit vector for control. Unit vectors ($\cos\theta_e$, $\sin\theta_e$) are generally generated using the flux vectors, but it can also be generated using voltage vectors. The name of the orientation of unit vector is given according to the vector taken for generation of $\theta_e$. The names of the orientations used are given below.

1. Rotor flux orientation
2. Stator flux orientation
3. Air gap flux orientation

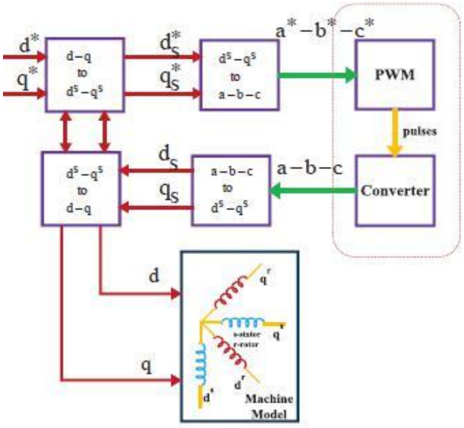

**Fig .24** Implementation of vector control principle

The detail vector control strategy is shown in above figure. The a, b, c components are generated from the controlled components a*, b*, c* respectively using vector control techniques. The machine terminal parameters (either voltages or currents) are converted to $d^s$-$q^s$ components by 3-phase to 2-phase transformation. These are then converted to synchronously rotating frame by the unit vector before applying to the 2-phase machine model. The controller makes two stage of inverse transformation as shown, so that the control components d* and q* corresponds to the machine parameters d and q respectively.

### *4.2.2 SYNCHRONISED MODEL OF GRID CONNECTED DOUBLY FED INDUCTION GENERATOR FOR WIND POWER GENERATION:*

### *MAGNITUDE AND FREQUENCY CONTROL OF DFIG:*

A magnitude and frequency control (MFC) strategy has been proposed for the grid connected doubly fed induction generator (DFIG).The proposed MFC makes the DFIG equivalent to a synchronous generator in the power system .The active and reactive powers of the stator depend on the phase and magnitude of the new equivalent _emf behind the internal transient reactance‘. The relationship between the rotor voltage and the _emf behind the internal transient reactance‘ is also detailed. Unlike traditional control strategies such as stator-flux-orientation vector control and FMAC, the MFC method manipulates the magnitude and frequency of the rotor voltage. This simplifies the design of the control system and improves system reliability. Thus, co-ordinate transformations, rotor position detection, and measurements of rotor currents and rotor speeds are not required [3].

### *SYNCHRONISED MODEL OF DFIG:*

### *MODELLING OF DFIG STATOR:*

It is assumed that the stator transient can be neglected in this paper. The effects of neglecting stator transients in DFIG model were analysed. Besides analysis, includes simulated waveforms which establish that the stator transients in DFIG can be neglected and the accuracy is not affected after the transients have damped out.

By neglecting the stator transient, the voltage equations of the DFIG in the arbitrary d-q reference frame can be expressed as follows (stator in generator convention and rotor in motor convention)

$ud1 = -r1d1 - \aleph q1\omega 1$ (38)

$uq1 = -r1q1 - \aleph d1\omega 1$ (39)

$ud2 = -r2id2 + \text{Ᵽ}\aleph d2 - \aleph q2\omega 2$ (40)

$uq2 = -r2iq2 + \text{Ᵽ}\aleph q2 - \aleph d2\omega 2$ (41)

The corresponding flux linkage equations:

$\aleph d1 = -L1id1 - Lmid2$ (42)

$\aleph q1 = -L1iq1 - Lmiq2$ (43)

$\aleph d2 = L2id2 - Lmid1$ (44)

$\aleph d2 = L2iq2 - Lmiq1$ (45)

Setting the d-axis to align with the rotor flux vector, one defines $\psi_2=\psi_{d2}$ . A consequence of the rotor flux alignment is $\psi_{q2}=0$.

Thus, rotor currents can be expressed in terms of stator currents as:

$id2 = (\aleph 2 + Lmid1)/L2$ (46)

$iq2 = Lm/L2iq1$

(47)

In order to eliminate the rotor variables in stator equations, define

$Eq` = \omega 1(Lm/L2)\aleph 2$ (48)

Where $E_{q`}$ is the equivalent _emf behind the internal transient reactance‘ which is generated by the rotor flux linkage $\psi_2$, and

$\sigma= (L_1L_2-L^2{}_m)/ L_1L_2$ is the leakage factor. (49)

By substituting, the stator voltage equations can be written as follows:

$ud1 = -r1id1 + X'1iq1$ (50)

$uq1 = -r1iq1 - X'1id1 + E'q$ (51)

Neglecting the stator resistance, the vector diagram of the DFIG stator can be drawn as shown in Fig 4.7 according to above equations.

In this vector diagram, δ is the power angle between the vector $\boldsymbol{E'_q}$ and $\boldsymbol{U_1}$ and ϕ is the phase angle between the vector $\boldsymbol{U_1}$ and $\boldsymbol{I_1}$. Based on Fig 4.7, the stator currents can be calculated as

$$id1 = (E'q - U1Cos\delta)/X'1 \quad (52)$$

$$iq1 = U1Sin\delta/X'1 \quad (53)$$

Then the equations of active and reactive powers of the DFIG stator:

$$P1 = U1I1Cos\varphi = (E'qU1)\frac{1}{X'1}Sin\delta \quad (54)$$

$$Q1 = U1I1Sin\varphi = \frac{E'qU1}{X'1Cos\delta} - U1^2/X'1 \quad (55)$$

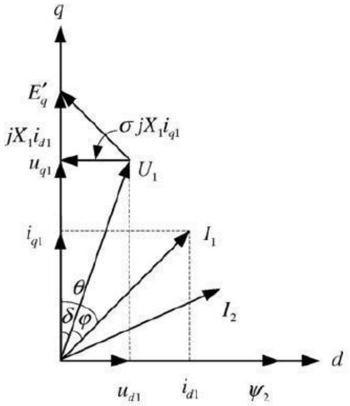

**Fig 25:** Vector diagram of the DFIG

It can be seen that the DFIG has the same expression of active and reactive powers as the synchronous machine. Developing from and adding the stator resistance r1, Fig: 4.11 is the single line equivalent circuit of the DFIG. It is similar to that of the synchronous generator except the excitation voltage is different, because it is controlled from a more complex rotor equivalent circuit.

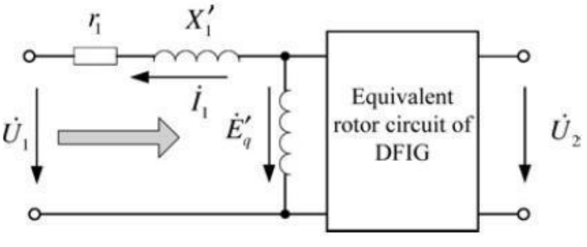

**Fig.25** Equivalent circuit of DFIG

The power angle in synchronous generator is relatively small in normal operation which is often below 30 degrees. This condition can be also met in DFIG. With this condition the classic synchronous generator theory indicates that the active power transfer depends mainly on the power angle and the reactive power transfer depends mainly on the voltage magnitude of E ’ q, respectively. By similarity of synchronous generator, the control of the stator active power and reactive power of the DFIG can be seen as the control of phase and magnitude of E′q . The DFIG has a benefit in that the power angle δ (and therefore the active power) is controllable by the rotor converter whereas δ in the synchronous generator is determined by the axis of the field winding.

### *4.4.2 MODELLING OF THE DFIG ROTOR:*

By substituting rotor flux equations into the rotor voltage equations, the rotor voltages can be expressed as:

$$Ud2 = r2\left(\frac{\aleph 2}{L2}\right) + r2\left(\frac{Lm}{L2}\right) + \text{Ᵽ}\aleph 2$$

(56)

$$Uq2 = r2\left(\frac{Lm}{L2}\right)iq1 + \aleph 2\omega 2$$

(57)

$$I1 = (E'q - U1)/X'1$$

(58)

$$U2 = \left(\left(\frac{r2Lm}{\sigma L2X1}\right) + \frac{r2}{Xm} + \left(\frac{\omega 2L2}{Xm}\right) + \text{Ᵽ}\right)E'q - \left(\frac{r2Lm}{\sigma L2X1}\right)U1 (59)$$

Equation above describes the relationship between the stator voltage vector U1, the rotor voltage vector U2 and the internal transient EMF vector . The stator voltage U1 is the same as the grid voltage and thus can be controlled by U2. Unlike the exciter of the synchronous generator which can only adjust the magnitude of the exciter voltage only, the rotor controller of the DFIG can manipulate both the magnitude and the phase angle of U2 vector. Thus, the active and reactive powers of the DFIG can be controlled by U2 vector.

### *MODELLING THE DFIG-BASED WIND TURBINE:*

The active power of the DFIG rotor can be expressed as:

$$P2 = ud2id2 + uq2iq2$$

(60)

Equation above can be re-expressed in the vector form as follows:

$$P2 = Pr2 + \omega 2/\omega 1P1$$

(61) )

Where Pr2=$r2id2^2 + r2iq2^2$

(62)

is the power losses associated with the rotor resistance, which is small enough to be ignored. It can be shown that the active power of the rotor depends on the rotor current frequency, stator frequency and the active power of the stator. Depending on the rotor speed $\omega_r$, the rotor current frequency, $\omega_2 = \omega_1 - \omega_r$, can be positive and negative and therefore the rotor power changes direction. The active power of the rotor is positive when the DFIG operates at the sub-synchronous mode ($\omega_1 > \omega_r$) and negative when the DFIG operates at the super-synchronous mode ($\omega_1 < \omega_r$). The grid-side converter, in maintaining the DC-link voltage regulated, feeds or absorbs the slip dependent rotor active power. The reactive power of the grid side converter is set to zero to give a unity displacement factor.

### *MECHANICAL EQUATION OF MOTION:*

The stator voltage vector $\boldsymbol{U_1}$ rotates at the speed of $\omega_1$ of the grid frequency. The rotating speed of E'q is the algebraic sum two speeds: the rotor speed $\omega_r$ and the rotor current angular frequency $\omega_2$. So the equation of the power angle is:

$$\delta' = (\omega r + \omega 2)\text{-}\omega 1 \qquad (63)$$

The equation of motion of the rotor is:

$$J\omega r' = Tm - Tem \qquad (64)$$

Where $T_m$ is the input torque from the wind turbine and $T_{em}$ is the electromagnetic torque of the DFIG. The flux linkage expressions in terms of current can be written from Fig.4.7 and Fig.4.8 as follows:

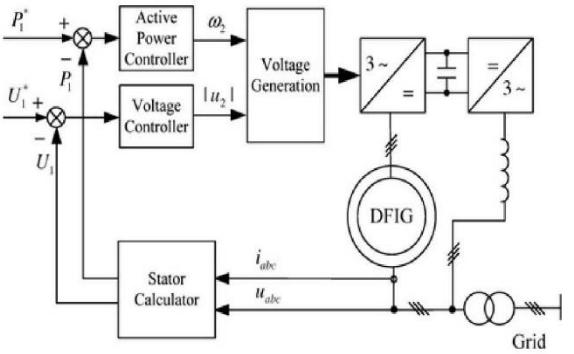

**Fig: 26** MFC Controller Diagram

## V. RESULT

### *5.1 PITCH CONTROL ANALYSIS BY MATLAB:*

Explanation:

$$Pm = (0.5Cp(\gamma,\beta)\rho AVw^3 \qquad (65)$$

Where

$\gamma$ is the tip speed ratio;
Pm is mechanical output power of the wind turbine;
$Cp\ (\gamma, \beta\ )$ is the performance coefficient of the turbine;
ρ is the density of air in kg/m3 ;
A is the swept area of turbine; Vw is the wind speed (m/s);
β pitch angle of blade in degrees;
A basic equation used to model Cp $(\gamma, \beta\ )$
β pitch angle of blade in degrees;

$$Cp\ (\gamma, \beta\ ) = \text{C1}\left(\frac{\text{C2}}{\gamma} - \text{C3}\beta - \text{C4}\right)\text{e}^{\frac{\text{cs}}{\gamma i}} + \text{C6}\gamma$$

and

$$1/\ \gamma i = \left(\frac{1}{\gamma + 0.08\beta}\right) - \left(\frac{0.035}{\beta^3} + 1\right)$$

The coefficients c1 to c6 are: c1 = 0.5176, c2 = 116, c3 = 0.4, c4 = 5, c5 = 21 and c6 = 0.0068. The Cp-λ characteristics, for different values of the pitch angle β, are illustrated below. The maximum value of Cp (Cpmax = 0.48) is achieved for β = 0 degree and for λ = 8.1. This particular value of λ is defined as the Nominal value (λ_nom).

### *PROGRAM*:

```
L=0.01:0.1:15;
c1=0.5176;
c2=116;
c3=0.4;
c4=5;
c5=21;
c6=0.0068;
pitch=0:5:25;
for i=1:6
        for p=1:length(L);
A(p)=1/(L(p)+0.08*pitch(i))-0.035/(pitch(i)^3+1);
C(p)=c1*(c2*A(p)-c3*pitch(i)-c4)*exp(-
c5*A(p))+c6*L(p);

        end
        plot(A(p),C(p));
        hold on;
end
axis ([0 15 -0.1 0.5]);
xlabel('\lambda'),ylabel('Cp');
```

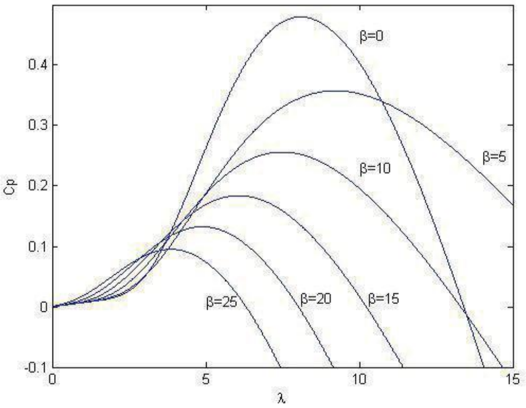

**Fig: 27** Power coefficients versus tip speed ratio

### *5.2 MECHANICAL CHARACTERISTICS ANALYSIS BY MATLAB*

### *PROGRAM:*

```
% mechanical_characteristics.m
%       numerical simulations of the power
coefficient of the wind turbine as a function of the
tip
% speed rate and the pitch angle.
c1=0.5176; c2=116; c3=0.4; c4=5; c5=21;
c6=0.0068; r0=1.29;D=40;
A=pi*D^2/4;L=0.01:0.1:15;b=0;
V=[8,10,12,14,16,18,20];
for k=1:length(V)
```

```
        for p=1:length(L);
                AI(p)=1/(L(p))-0.035;
                CP(p)=c1*(c2*AI(p)-c4)*exp(-
                c5*AI(p))+c6*L(p);
                P(k,p)=(V(k)^3)*CP(p)*r0*A/2;
                n(k,p)=(60/(pi*D))*AI(p)*V(k);
        end;

        hold on;
end;
M=max(P(6,:)); m=max(M); P=P/m; n1=length(L);
n2=length(V); for j=1:n1;
        P(:,n1-j+1)=P(:,j);
end;
PR=P;
for q=1:n2;
        plot(n(q,:), PR(q,:)); hold on
end;
grid; axis([0.1,1.45,-0.1,1.4]);
xlabel('rotational speed(relative
units)'),ylabel('power (relative units)');
```

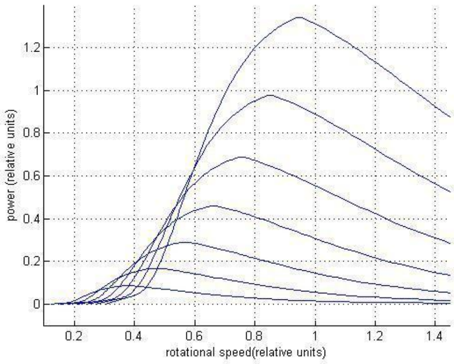

**Fig: 28** Wind turbine output power vs. rotational speed, with wind speed as parameter

### *5.3 TORQUE-SLIP CHARACTERISTICS*

Torque-slip characteristic when the angle of $V_r$ is 0. $|V_r|$ is changing from -0.05 to +0.05 pu:

MATLAB code:

```
Xls=0.0135;
Xlr=0.0075;
rs=0.00059;
rr=0.00339;
Vs=0.5;
Vr=-0.05:0.01:0.05;
for i=1:11
        s=-1:0.01:1;
        for j=1:201
                T(i,j)=(s(j)*Vs^2-
Vs*Vr(i))*(s(j)*rs+rr)/((s(j)*rs+rr)^2+s(j)^2*(Xls+
Xlr)^2);
        end;
        plot(s,T);
end;
axis([-1,1,-15,15])
xlabel('slip'),ylabel('Torque (pu)');
```

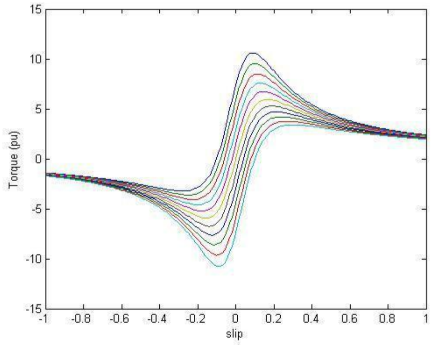

**Fig: 29** Torque-slip characteristic when the angle of Vr is 0.

### *TORQUE-SLIP CHARACTERISTIC WHEN $|V_r|$ IS 0.05 pu. THE ANGLE OF $V_r$ IS CHANGING FROM -90 TO +90*

MATLAB code:

```
clc;
clear all;
Xls=0.0135;
Xlr=0.0075;
rs=0.00059;
rr=0.00339;
Vs=0.5;

Vr=0.05;
angle_deg=-90:20:90;
angle_rad=deg2rad(angle_deg);
for i=1:length(angle_deg)
        s=-1:0.01:1;
        for j=1:201
                T(i,j)=(((s(j)*Vs^2-
Vs*Vr*cos(angle_rad(i)))*(s(j)*rs+rr))+(Vs*Vr*s(j)
*(Xls+Xlr)*sin(angle_rad(i))))/((s(j)*rs+rr)^2+s(j)^2
*(Xls+Xlr)^2);
        end;
        plot(s,T);
end;
% axis([-1,1,-15,15])
xlabel('slip'),ylabel('Torque(pu)');
```

|Vr| is changing from -0.05 to +0.05 pu.

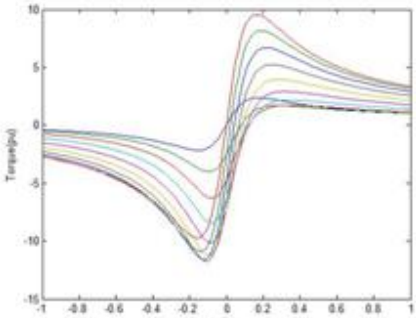

**Fig: 30** Torque-slip characteristic when |Vr| is 0.05 pu. The angle of Vr is changing from - to

### *5.3 STUDY OF WTDFIG IN A 9MW WIND FARM CONNECTED TO A 25KV, 60 HZ SYSTEM*

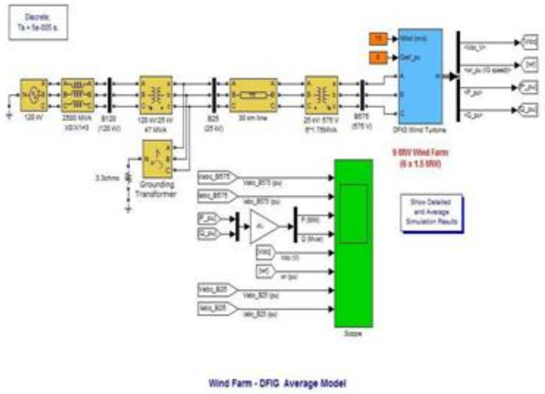

**Fig: 31** Wind farm DFIG Average Model

### *SIMULATION RESULTS OF DFIG AVERAGE MODEL*

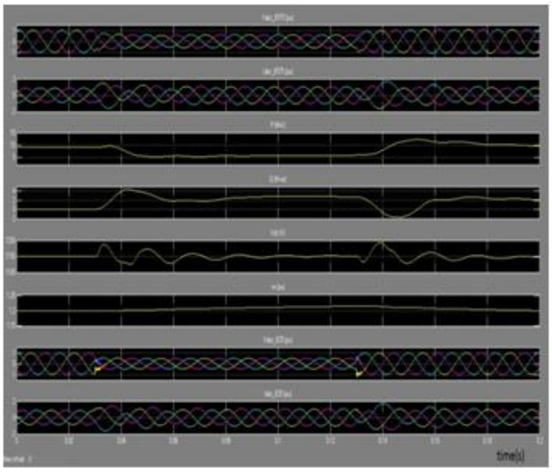

**Fig: 32** Simulation results of DFIG average model

### *5.4 SIMULINK MODEL FOR MAGNITUDE AND FREQUENCY CONTROL OF DFIG:*

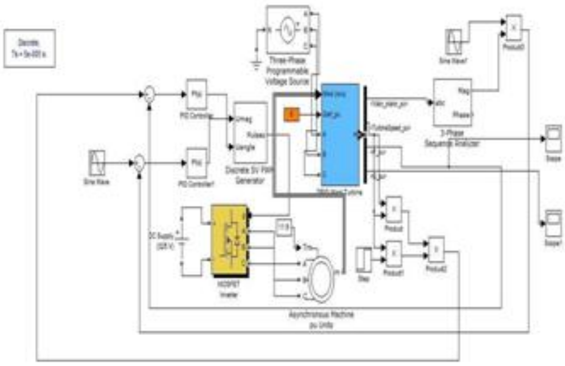

**Fig: 33** Simulink model for MFC

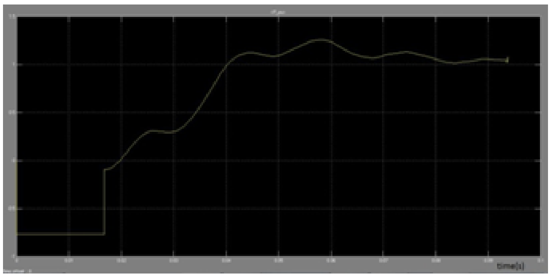

**Fig.34** Active Power

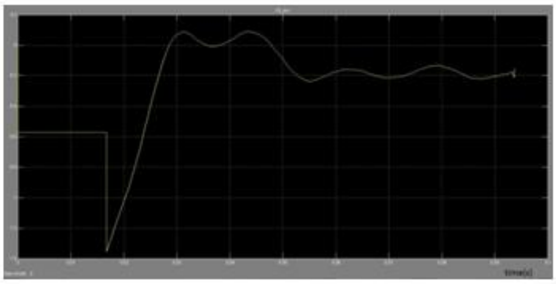

**Fig.35** Reactive Power

## VI. CONCLUSIONS

DFIGs are enormously used in Wind farms because of their ability to supply power at constant voltage and frequency.Charactristics of DFIG are studied in MATLAB environment. Control techniques of DFIG have been analysed. Magnitude and Frequency control has been studied and a Simulink model for the same has been proposed. Unlike traditional methods like Stator flux orientation vector control and FMAC, the MFC method manipulates the magnitude and frequency of the rotor voltage. This simplifies the design of the control system and improves system reliability.

## ACKNOWLEDGEMENT

I would like to thank my parents for giving their support throughout my life.

## REFERENCES

[1]. GTZ (2000) Wind Energy Projects in Morocco and Namibia.Eschborn, retrieved 08.01.2013 https://www.docstoc.com/pass/22042181]

[2]. GTZ (2000) Wind Energy Projects in Morocco and Namibia. Eschborn, retrieved 08.01.2013 [1]

[3]. Kaldellis J.K. (2010) Overview of stand-alone and hybrid wind energy systems, in: Kaldellis J.K. (2010) Stand-alone and hybrid wind energy systems, Woodhead publishing

[4]. GTZ (2009) TERNA Wind Energy Programme 1997-2009 – Impact Report –. Eschborn, Germany, retrieved 25.7.2011 [[2]]

[5]. GTZ (2007): Eastern Africa Resource Base: GTZ Online Regional Energy Resource Base:

Regional and Country Specific Energy Resource Database: I - Energy Technology.
[6]. GTZ 2009: Technical and Economic Potential of Wind-Powered Water Desalination. TERNA Wind Energy Programme. Eschborn, retrieved 25.7.2011 [[3]]
[7]. GTZ (2000) Wind Energy Projects in Morocco and Namibia. Eschborn, retrieved 08.01.2013 [4]
[8]. World Wind Energy Association / GTZ: Wind Energy in Developing and Emerging Countries, retrieved 25.7.2011 [[5]]
[9]. http://web.mit.edu/windenergy/windweek/Presentations/Wind%20Energy%20101.pdf
[10]. Indian wind energy outlook 2011,‖ Global wind Energy council, April, 2011.
[11]. Sherihan Ashraf Shaheen, Hany M. Hasanien , and M. Abd-El-Latif Badr, ―Study on Doubly Fed Induction Generator Control‖ , IEEE press,2010.
[12]. Z. Wang, Y. Sun, G. Li and B.T. Ooi, ―Magnitude and frequency control of gridconnected doubly fed induction generator based on synchronised model for wind power generation‖ , IET Renewable Power generation, 2010.
[13]. Zhixin Miao ,Yuvarajan S, GlowerJ, ―A comparison of slip control, FMA control and vector control in DFIG converter‖, IECON 2008, 34th Annual Conference of IEEE,2008.
[14]. Satish Choudhury, Kanungo Barada Mohanty, B.Chitti Babu, ―Performance Analysis of Doubly-Fed Induction Generator for Wind Energy Conversion System‖, Proc. PSUUNS International Conference on Engineering and Technology (ICET-2011), Phuket, Thailand, pp.532-536, May 2011.
[15]. S. N. Bhadra, D. Kastha, S. Banerjee, ―Wind Electrical Systems‖, Oxford University Press, New Delhi, 2009.
[16]. O. A. Lara, N. Jenkins, J. Ekanayake, P.Cartwright, M. Hughes, ―Wind energy generation: Modeling and Control‖, John Wiley and Sons, UK, 2009.
[17]. Nicholas W. Miller, Juan J. Sanchez-Gasca, William W. Price, Robert W. Delmerico, "Dynamic modelling of GE 1.5 and 3.6 mw wind turbine-generators for stability simulations," GE Power Systems Energy Consulting, IEEE WTG Modelling Panel, Session July 2003.
[18]. Global Wind Report”, Global Wind Energy Council, 2011.

T.Divyapradeepa "Wind Energy Using Doubly Fed Induction Generator.” International Journal of Engineering Research and Applications (IJERA) , vol. 7, no. 12, 2017, pp. 49-67.