Study of Wind Energy System with Induction Generators

a thesis submitted in partial fulfilment of the requirements for the degree of

Bachelor of Technology
In
Electrical Engineering

by

Pusyakant Tiwari (107EE037)
Dhananjay Swain (107EE057)
K. Anil Kumar (107EE064)

Under the guidance of

Prof. K. B. Mohanty

Department of Electrical Engineering
National Institute of Technology
Rourkela

National Institute of Technology
Rourkela

CERTIFICATE

This is to certify that the thesis entitled, "Study of Wind Energy System with Induction Generators" submitted by Pusyakant Tiwari, Dhananjaya Swain, K. Anil Kumar in partial fulfilment of the requirements for the award of Bachelor of Technology Degree in Electrical Engineering at the National Institute of Technology, Rourkela (Deemed University) is an authentic work carried out by them under my supervision.

And to the best of my knowledge, the matter embodied in the thesis has not been submitted to any other University/Institute for the award of any Degree or Diploma.

(Prof. K. B. Mohanty)

Dept. of Electrical Engineering.

National Institute of technology

Rourkela-769008

Date:

ACKNOWLEDGEMENT

We would like to articulate our deep gratitude to our project guide **Prof. K.B. Mohanty** who has always been source of motivation and firm support for carrying out the project.

We express our gratitude to **Prof. B. D. S**ubudhi, Professor and Head of the Department, ELECTRICAL Engineering for his invaluable suggestions and constant encouragement all through the thesis work. We would also like to convey our sincerest gratitude and indebtedness to all other faculty members and staff of Department of Electrical Engineering, NIT Rourkela, who bestowed their great effort and guidance at appropriate times without which it would have been very difficult on our project work.

We owe a special thanks to our friends Mahendra Pratap Singh, M.V Ashwin Kumar and Sriharsha Ramineni for their valuable suggestions and help during the course of the project.

An assemblage of this nature could never have been attempted with our reference to and inspiration from the works of others whose details are mentioned in references section. We acknowledge our indebtedness to all of them. Further, we would like to express our feeling towards our parents and God who directly or indirectly encouraged and motivated us during this dissertation.

Pusyakant Tiwari (107EE037)

Dhananjaya Swain (107EE057)

K. Anil Kumar (107EE064)

CONTENTS

LIST OF FIGURES

ABSTRACT

Wind energy, as an alternative to fossil fuels, is plentiful, 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. They are also competitive with fossil fuel generated power and much cheaper than nuclear power.

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.

CHAPTER 1

WIND ENERGY- AN OVERVIEW

INTRODUCTION

The conventional energy sources are limited and pollute the environment. So more attention and interest have been paid to the utilization of renewable energy source such as **Wind Energy, Fuel Cell, Solar Energy etc.,** Wind Energy is the fastest growing and most promising renewable energy source among them as it is economically viable.

1.1 WIND ENERGY IN INDIA

In 2008, India was the country that brought online the third largest amount of wind energy, after the US and China, and it now ranks fifth in total installed capacity with 9,645 MW of wind power installed at the end of 2008. A strong domestic manufacturing base has underpinned the growth of the Indian wind energy market.

The Indian wind turbine manufacturer Suzlon is now a recognised player on the global market and many international companies are established in India. India has a great untapped potential for wind energy.

A strong domestic manufacturing base has underpinned the growth of the Indian wind energy market.

India has a great untapped potential for wind energy. According to official estimates, the Country's total wind energy resource amounts to **48 GW** of installed capacity, but some experts think that this figure is on the conservative side, and that technological improvements could significantly increase this potential.

The positive development of wind energy in India has mainly been driven by progressive state level legislation, including policy measures such as renewable portfolio standards and feed-intariffs. At the moment, there is no coherent national renewable energy policy to drive the development of wind energy. This is urgently needed to realize the country's full potential and reap the benefits for both the environment and the economy.

The Government of India is currently considering the introduction of a national renewable energy policy, so this report comes as a timely reminder of how important a role wind energy could play in securing India's energy security, curbing its CO_2 emissions, providing new employment and boosting economic development.

This also realizes how important a role wind energy could play in securing India's energy security, curbing its CO_2 emissions, providing new employment and boosting economic development. As can be seen by the Indian Wind Energy Outlook, the wind industry, both domestic and international, stands ready to do its part in achieving an energy revolution in India.

1.2 ECONOMY OF WIND ENERGY IN INDIA

In the early 1980s, the Indian government established the Ministry of Non-Conventional Energy Sources (MNES) to encourage diversification of the country's energy supply, and satisfy the increasing energy demand of a rapidly growing economy. In 2006, this ministry was renamed the Ministry of New and Renewable Energy (MNRE). Renewable energy is growing rapidly in India. With an installed capacity of **13.2 GW**, renewable energy sources (excluding large hydro) currently account for **9%** of India's overall power generation capacity.

By 2012, the Government of India is planning to add an extra 14 GW of renewable resources in its 10th Five Year Plan. The Government of India had set itself a target of adding 3.5 GW of renewable energy sources to the generation mix. In reality, however, nearly double that figure was achieved. In this period, more than **5.4 GW** of wind energy was added to the generation mix, as well as 1.3 GW from other Resources.

The Indian Ministry of New and Renewable Energy (MNRE) estimates that there is a potential of around 90,000 MW for the country, including **48,561 MW** of wind power, 14,294 MW of small hydro power and 26,367 MW of biomass In addition, the potential for solar energy is estimated for most parts of the country at around 20 MW per square kilometre of open, shadow free area covered with 657 GW of installed capacity.

1.3 WIND POTENTIAL

The total potential for wind power in India was first estimated by the Centre for Wind Energy Technology (C-WET) at around 45 GW, and was recently increased to 48.5 GW. This figure was also adopted by the government as the official estimate.

The C-WET study was based on a comprehensive wind mapping exercise initiated by MNRE, which established a country-wide network of 105O wind monitoring and wind mapping stations in 25 Indian States. This effort made it possible to assess the national wind potential and identify suitable areas for harnessing wind power for commercial use, and 216 suitable sites have been identified.

However, the wind measurements were carried out at lower hub heights and did not take into account technological innovation and improvements and repowering of old turbines to replace them with bigger ones At heights of 55-65 meters, to replace them with Bigger ones. At heights of 55-65 meters, the Indian Wind Turbine Manufacturers Isolation (IWTMA) estimates that the potential for wind development in India is around 65-70 GW. The World Institute for Sustainable Energy, India (WISE) considers that with larger turbines, greater land availability and expanded resource exploration, the potential could be as big as 100 GW. Wind power in India has been concentrated in a few regions, especially the Southern state of Tamil Nadu, which maintains its position as the state with the most wind power, with 4.1 GW installed at the end of 2008, representing 44% of India's total wind capacity.

1.4 WIND FARMS IN INDIA

1. Muppandal–Perungudi (Tamil Nadu)

With an aggregate wind power capacity of 450 MW, the Muppandal –Perungudi region near Kanyakumari in Tamil Nadu has the distinction of having one of the largest clusters of wind turbines. About Rs 2500 crores has been invested in wind power in this region.

2. Kavdya Donger, Supa (Maharashtra)

A wind farm project has been developed at Kavdya Donger at Supa, off the Pune–Ahmednagar highway, about 100 km from Pune. This wind farm has 57 machines of 1-MW capacity each. Annual utilization capacity of up to 22% has been reported from this site. The farm is connected through V-SAT to project developers as well as promoters for online performance monitoring.

3. Satara district (Maharashtra)

Encouraging policy for private investment in wind power projects has resulted in significant wind power development in Maharashtra, particularly in the Satara district. Wind power capacity of about 340 MW has been established at Vankusawade, Thosegarh, and Chalkewadi in Satara district, with an investment of about Rs.1500 crores.

CHAPTER 2:

FUNDAMENTALS OF WIND TURBINES.

.

2.1 Power in the wind.

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.

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:

$$\mathbf{P_w = 0.5\rho\pi R^2 V^3 C_p(\lambda,\beta)} \qquad \text{Equation 2.1}$$

P_w = extracted power from the wind,

ρ = air density, (approximately 1.225 kg/m^3 at 20° C at sea level)

R = blade radius (in m), (it varies between 40-60 m)

V_w = wind velocity (m/s) (velocity can be controlled between 3 to 30 m/s)

C_p = the power coefficient which is a function of both tip speed ratio (λ), and blade pitch angle, (β) (Degrees)

Power coefficient (C_p) is defined as the ratio of the output power produced to the power available in the wind.

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%.

2.2. 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 (WEC), or aerogenerator.

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.

1. Horizontal axis wind turbine

    a.) ‘Dutch-type’ grain grinding windmills.

    b.) Multi-blade water-pumping windmills.

    c.) High speed propeller type windmills.

2. Vertical axis wind turbine

    a.) The Savonius rotor.

    b.) The Darrieus rotor.

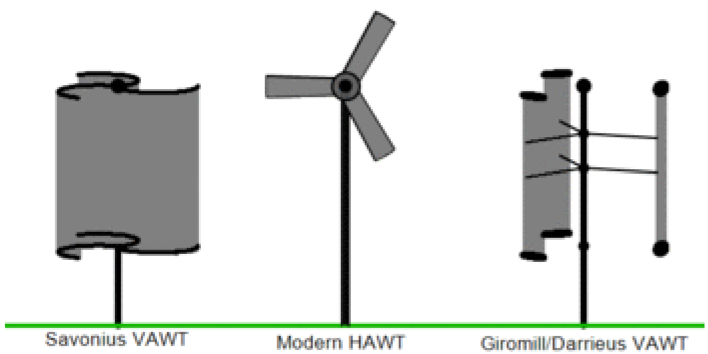


Figure 2.1 – Different wind turbines.

A. Horizontal Axis Wind Turbine

Horizontal-axis wind turbines (HAWT) have the main rotor shaft and electrical generator at the top of a tower, and must be pointed into the wind. Most have a gearbox, which turns the slow rotation of the blades into a quicker rotation that is more suitable to drive an electrical generator. Since a tower produces turbulence behind it, the turbine is usually pointed upwind of the tower. Turbine blades are made stiff to prevent the blades from being pushed into the tower by high winds. Additionally, the blades are placed a considerable distance in front of the tower and are sometimes tilted up a small amount.

Downwind machines have been built, despite the problem of turbulence, because they don't need an additional mechanism for keeping them in line with the wind, and because in high winds the blades can be allowed to bend which reduces their swept area and thus their wind resistance. Since cyclic (that is repetitive) turbulence may lead to fatigue failures most HAWTs are upwind machines.

High-speed Propeller-type Wind Machines.

The horizontal-axis wind turbines that are used today for electrcity generation don't operate on thrust force, but on the aerodynamic forces that develop when wind flows around a blade of aerofoil design. Actually, the windmills that work on thrust forces are less efficient.

Aerofoil

The wind stream at the top of the aerofoil has to traverse a longer path than that at the bottom, leading to a difference in velocities.This gives rise to a difference in pressure (bernoulli's principle), and a lift force is produced. There is also a drag force that tries to push the aerofoil back in the direction of the wind. The aggregate force is determined by the resultant of these forces .

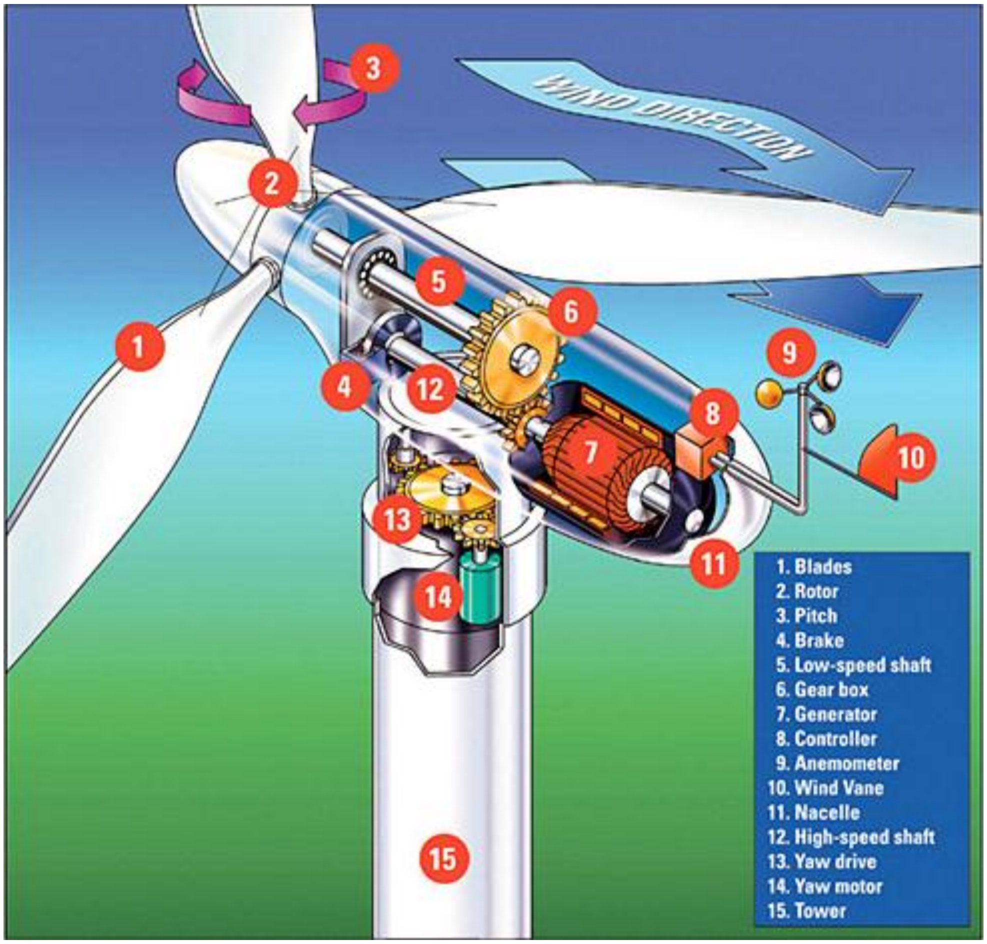


Figure: Various parts in a Horizontal Axis Wind Turbine- propeller type.

Figure 2.2

Advantages of HAWT:

• Variable blade pitch, which gives the turbine blades the optimum angle of attack. Allowing the angle of attack to be remotely adjusted gives greater control, so the turbine collects the maximum amount of wind energy for the time of day and season.

• The tall tower base allows access to stronger wind in sites with wind shear. In some wind shear sites, every ten meters up, the wind speed can increase by 20% and the power output by 34%.

• High efficiency, since blades always move perpendicularly to the wind, receiving power through the whole rotation. In contrast, all vertical axis wind turbines, and most proposed airborne wind turbine designs, involve various types of reciprocating actions, requiring aerofoil surfaces to backtrack against the wind for part of the cycle. Backtracking against the wind leads to inherently lower efficiency.

Disadvantages of HAWT:

• The tall towers and blades up to 90 meters long are difficult to transport. Transportation can now cost 20% of equipment costs.

• Tall HAWTs are difficult to install, needing very tall and expensive cranes and skilled operators.

• Massive tower construction is required to support the heavy blades, gearbox, and generator.

• Reflections from tall HAWTs may affect side lobes of radar installations creating signal clutter, although filtering can suppress it.

• Downwind variants suffer from fatigue and structural failure caused by turbulence when a blade passes through the tower's wind shadow (for this reason, the majority of HAWTs use an upwind design, with the rotor facing the wind in front of the tower).

• HAWTs require an additional yaw control mechanism to turn the blades toward the wind.

B. VERTICAL AXIS WIND TURBINE

Vertical-axis wind turbines (or VAWTs) have the main rotor shaft arranged vertically. Key advantages of this arrangement are that the turbine does not need to be pointed into the wind to be effective. This is an advantage on sites where the wind direction is highly variable. VAWTs can utilize winds from varying directions. With a vertical axis, the generator and gearbox can be placed near the ground, so the tower doesn't need to support it, and it is more accessible for maintenance. Drawbacks are that some designs produce pulsating torque. Drag may be created when the blade rotates into the wind.

1. Savonius rotor.

The savonius rotor is an extremely simple vertical- axis device that entirely because of the thrust force of the wind. The basic equipment is a drum cut into two halves vertically. The two parts are attached to the two opposite sides of a vertical shaft. The wind blowing into the assembly meets two different surfaces- convex and concave- and different forces are exerted on them, giving torque to the rotor.

Providing a certain overlap between drums increases the torque because wind blowing on the concave side turns around and pushes the inner surface of the other drum, which partly cancels the wind thrust on the convex side. An overlap of one- third of the drum diameter gives best results.

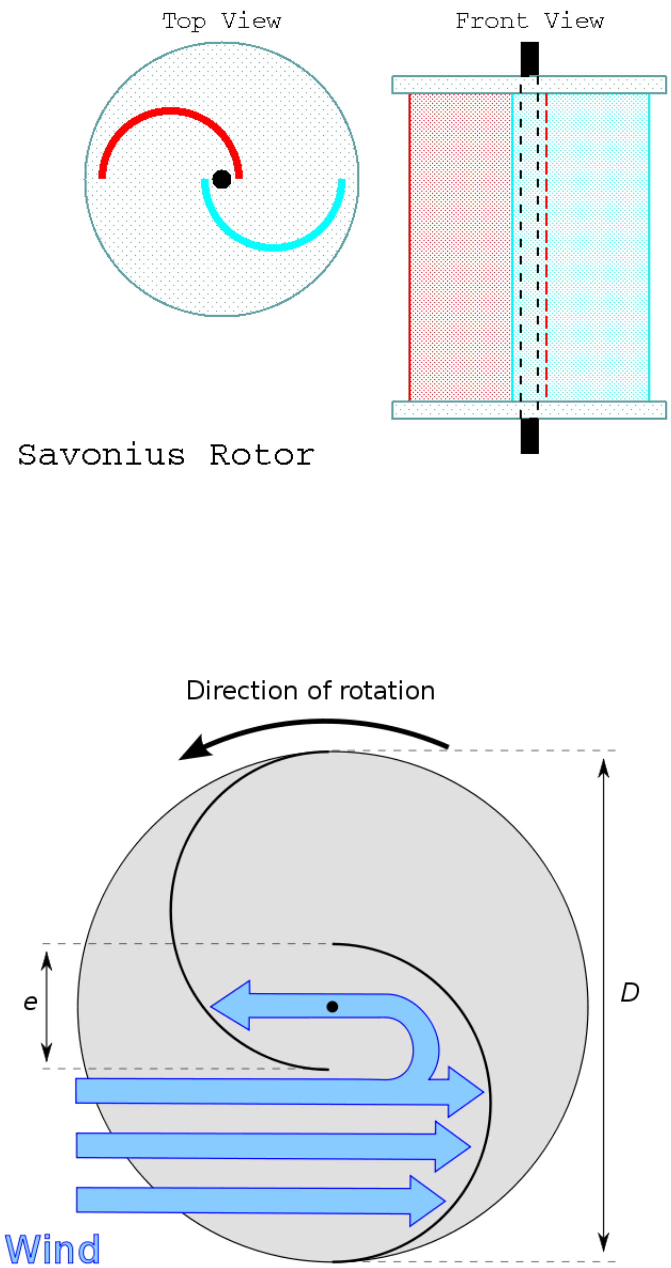


Figure 2.3 – The Savonious rotor

2. Darrieus Rotor:

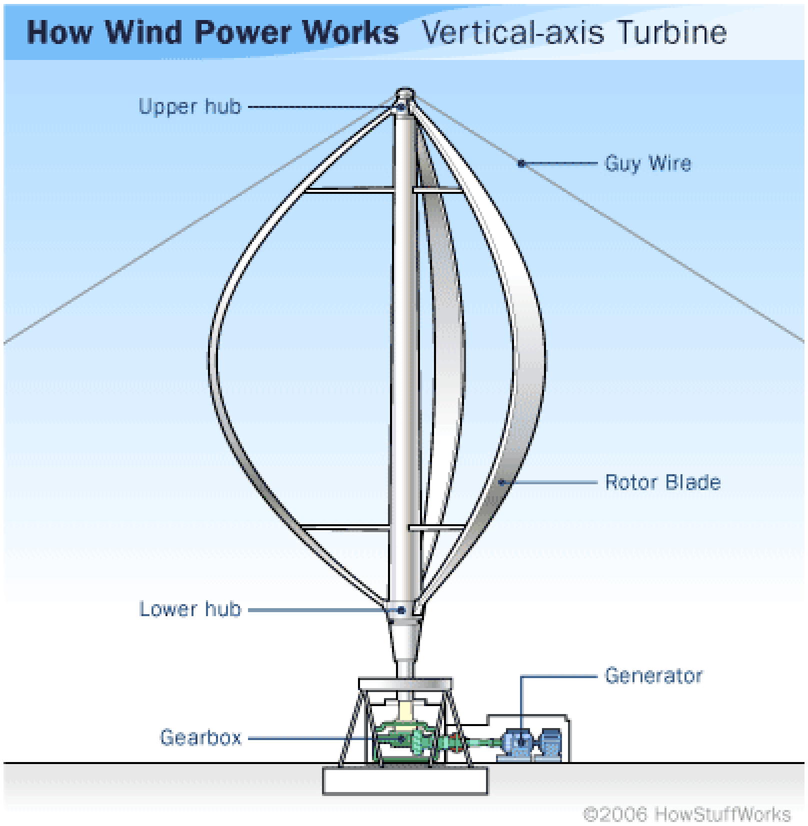


Figure 2.4 – Darrieus Wind Turbine

In a darrieus rotor, two or more flexible blades are attached are attached to a vertical shaft. The blades bow outward taking the shape of a parabola, and are of a symmetrical aerofoil section. When the rotor is stationary no torque is produced. It has to be started by some external means as it has no starting torque. The principle of operation is given in the figure.

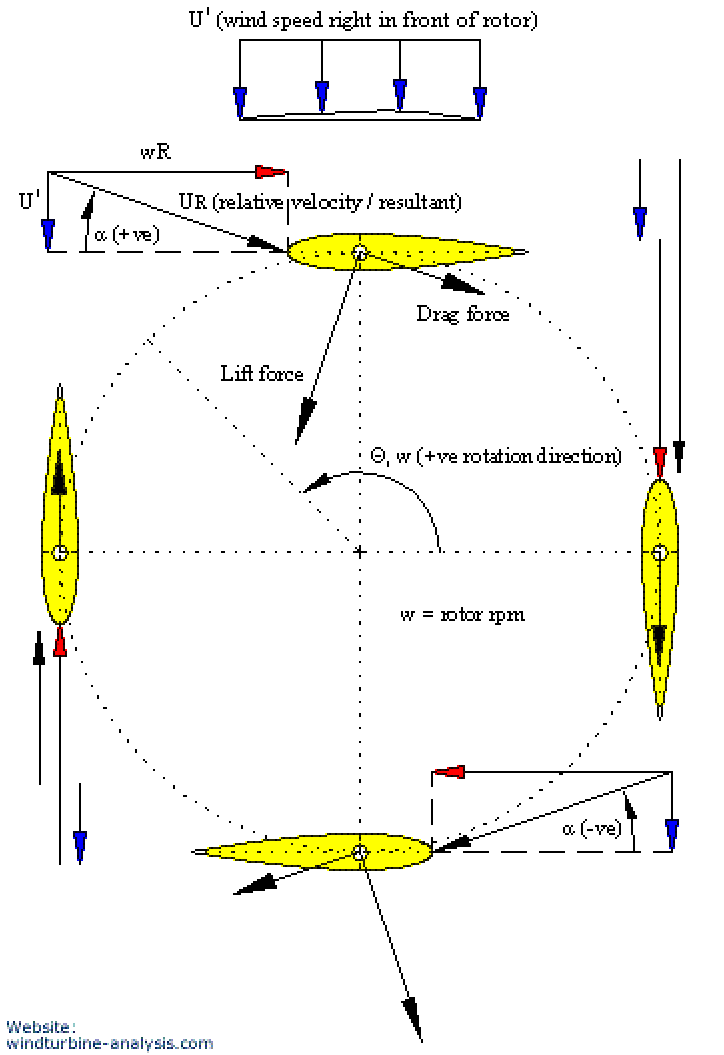


Figure 2.5 – Forces acting on a blade of the Darrieus rotor

At each position the lift force has a positive component in the direction of rotation, giving rise to net positive torque. The torque is different in different directions. It varies from zero to maximum in about a quarter of a revolution. The torque makes two complete excursions from zero to maximum and back in each revolution-both in positive sense. The pulsations in the shaft torque can be minimized by using a three blade system. However, the two blade design has lower erection cost.

The torque here is function of speed of rotation and the wind speed. The torque increases with rotational speed, and is zero at zero rotational speed. Torque increases with wind speed up to a certain value and then falls off at very high wind speeds. Therefore, this has inbuilt protection from stormy weather- the rotor tends to stall at high winds.

As the darrieus rotor operates on the lift force, its efficiency approaches that of modern horizontal- axis propeller-type windmills. The theoretical limit of power extraction can be shown to be 0.554 times the power in the wind; the corresponding betz limit for a horizontal-axis machine is 0.593.

The Darrieus rotor, with its efficiency and high speed, is perfectly suited for electrical power generation. The cost of construction is low because the generator and the gear assembly can be located at the ground level, drastically reducing the cost of the tower. However, it is unable to take advantage of the winds speeds available at the higher altitudes.

An electrical machine provides the starting torque running as motor, but changing to generating mode as the rotor starts generating power.

Advantages of VAWT

• A massive tower structure is less frequently used, as VAWTs are more frequently mounted with the lower bearing mounted near the ground.

• Designs without yaw mechanisms are possible with fixed pitch rotor designs.

• A VAWT can be located nearer the ground, making it easier to maintain the moving parts.

• VAWTs have lower wind start-up speeds than HAWTs. Typically, they start creating electricity at 6 M.P.H. (10 km/h).

• VAWTs may have a lower noise signature.

Disadvantages of VAWT

• Most VAWTs produce energy at only 50% of the efficiency of HAWTs in large part because of the additional drag that they have as their blades rotate into the wind.

• While VAWTs' parts are located on the ground, they are also located under the weight of the structure above it, which can make changing out parts nearly impossible without dismantling the structure if not designed properly.

• Having rotors located close to the ground where wind speeds are lower due to wind shear, VAWTs may not produce as much energy at a given site as a HAWT with the same footprint or height.

• Because VAWTs are not commonly deployed due mainly to the serious disadvantages mentioned above, they appear novel to those not familiar with the wind industry. This has often made them the subject of wild claims and investment scams over the last 50 years.

2.3 Some Relevant definitions

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 does not mean the actual blade area; it is the blade area met by the wind or projected in the direction of the wind.

The solidity of the Savonious rotor is natural unity, as the wind sees no free passage through it. For a multiple blade water-pumping windmill, it is typically around 0.7. For high-speed horizontal axis machines, it lies between 0.01 and 0.1; for the Darrieus rotor also it is of the same order.

Solidity has a direct relationship with the torque and speed. High-solidity rotors have high torque and low speed, and are suitable for pumping water. Low-solidity rotors, on the other hand, have high speed and low-torque, and are typically suited for electrical power generation.

Tip Speed Ratio:

The tip speed ratio (TSR) of a wind turbine is defined as

$$\boldsymbol{\lambda} = \frac{\boldsymbol{2\pi RN}}{\boldsymbol{V_{\infty}}}$$

Equation 2.2

Where $\boldsymbol{\lambda}$ is the TSR (non-dimensional), R is the radius of the swept area (in metres), N is the rotational speed in revolutions per second, and V_{∞} is the wind speed without rotor interruption (in metres per second).

The TSRs of the Savonious rotor and the multiple blade water-pumping windmills are generally low. In high-speed horizontal-axis rotors and Darrieus rotors, the outer tip actually turns much faster than the wind speed owing to the aerodynamic shape. Consequently, the TSR can be as high as 9. It can be said that high-solidity rotors have, in general, low TSRs and vice versa.

Power Coefficient:

The power coefficient of a wind energy converter is given by

$$C_p = \frac{power\ output\ from\ the\ wind\ machine}{power\ contained\ in\ the\ wind}$$

Equation 2.3

The power coefficient differs from the efficiency in the sense that the latter includes the losses in mechanical transmission, electrical generation etc., whereas the former is just the efficiency of conversion of wind energy into mechanical energy of the shaft. In high-speed horizontal-axis machines, the theoretical maximum power coefficient is given by the Betz limit.

Wind turbine ratings and specifications:

Since a wind turbine can produce varying amounts of electrical power depending on the wind speed, a standard procedure must be developed to specify the rating of a machine. One index used to compare various wind turbine designs is the *specific rated capacity (SRC),* defined as

$$SRC = \frac{power\ rating\ of\ the\ generator}{rotor\ swept\ area}$$

Equation 2.4

The SRC varies between 0.2 for small rotors to 0.6 for large ones.

Choice of the number of blades:

Efficiency of power extraction depends on the proper choice of the number of blades. There will be little power extraction if the blades are so close to each other or rotate so fast that every blade moves into a turbulent air caused by the preceding blade. It will also be less than the optimum if the blades are so far apart or move so slowly that much of the air stream passes through the wind turbine without interacting the blade. Thus, the number of blades should depend on TSR. Let $t_a$be the time taken by one blade to move into the position occupied by the previous blade. For an n- bladed rotor rotating at an angular velocity ώ,

$$t_a = 2\pi / n \acute{\omega}$$

Equation 2.5

Let t_b be the time taken by the disturbed wind, caused by the interference of the blade to move away and normal air to be re-established. It depends on the wind speed v and the length of the strongly perturbed wind stream, say d. This length depends on shape and size of blades:

$$t_b = d/v$$

Equation 2.6

For maximum power extraction t_a and t_b should both be approximately equal, so

$$\acute{\omega} / v = 2\pi / nd$$

Equation 2.7

For modern electricity-generating turbines, the empirical measurement of d and the requirement of a high TSR lead to a small number of blades, generally only two or three.

Though both 2- blades and 3- blades design are equally popular, the choice is dependent on some factors. The less nacelle weight and simplicity in erection are positive points of 2- blade turbine.

In three-blade turbines 33% more weight and cost is involved, but the power coefficient improves by 5-10%. The 3- blade systems have a smooth power output, less blade fatigue and less chances of failure.

Capacity Factor:

The term Capacity factor refers to the capability of a wind turbine to produce energy in an year. It is defined as the ratio of the actual energy output to the energy that would be produced if it is operated at rated power throughout the year.

$$\boldsymbol{Capacity\ factor = \frac{annual\ energy\ output}{rated\ power\ \times time\ in\ an\ year}}$$

Equation 2.8

2.4 Power speed characteristics:

The wind turbine power curves shown in figure illustrate how the mechanical power that can be extracted from the wind depends on the rotor speed. For each wind speed there is an optimum turbine speed at which the extracted wind power at the shaft reaches its maximum. Such a family of Wind turbine power curves can be represented by a single dimensionless characteristic curve namely the C_p- $\boldsymbol{\lambda}$ curve, as in the figure, where the power coefficient is plotted against the TSR For a given turbine, the power coefficient depends not only on the TSR but also on the blade pitch angle. Figure shows the typical variation of the power coefficient with respect to the TSR $\boldsymbol{\lambda}$ with the blade pitch control. The mechanical power transmitted to the shaft is

$$P_m = \frac{1}{2}\rho C_p A V_\infty^3$$

Equation 2.9

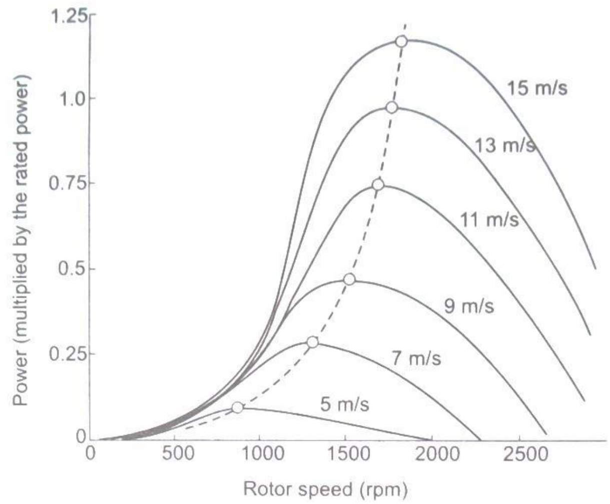


Figure 2.6 Power Speed Characteristics of Wind Turbine

Where C_p is the function of TSR $\boldsymbol{\lambda}$ and the pitch angle α.

For a wind turbine with radius R, it can be expressed

$$\boldsymbol{P_m = \frac{1}{2}\rho C_p \pi V_\infty^3 R^2}$$

Equation 2.10

For a given wind speed, the power extracted from the wind is maximized if C_p is maximized. The optimum value ofC_p, say $C_{p,pot}$, always occurs at a definite value of $\boldsymbol{\lambda}$, sayλ_{opt}. This means that for varying wind speed, the rotor speed should be adjusted proportionally to adhere always to this value of $\boldsymbol{\lambda}$=λ_{opt}, for the maximum power output from the turbine. Using the relation

$\boldsymbol{\lambda}$= ώR/ V_∞

Equation 2.11

The maximum value of the shaft mechanical power for any wind speed can be expressed as

$$P_{max} = 0.5\ C_{p,pot}\pi\ (R^5/\lambda_{opt}^3)\ \acute{\omega}^3$$

Equation 2.12

Thus the maximum mechanical power that can be extracted from the wind is proportional to the cube of the rotor speed, i.e., P_{max} is proportional to $\acute{\omega}^3$.

2.5 Torque speed characteristics

Studying the torque versus rotational speed characteristics of any prime mover is very important for properly matching the load and ensuring stable operation of the electrical generator. The typical torque speed characteristics of the two – blade propeller- type wind turbine, the Darrieus rotor, and the Savonius rotor are shown in figure. The profiles of the Torque-speed curves shown in the figure follow from the power curves, since torque and power are related as follows

$$T_m = P_m / \mathrm{w}$$

Equation 2.13

From the equation, at optimum operating point ($C_{p,pot}, \lambda_{opt}$), the relation between the aerodynamic torque and rotational speed is,

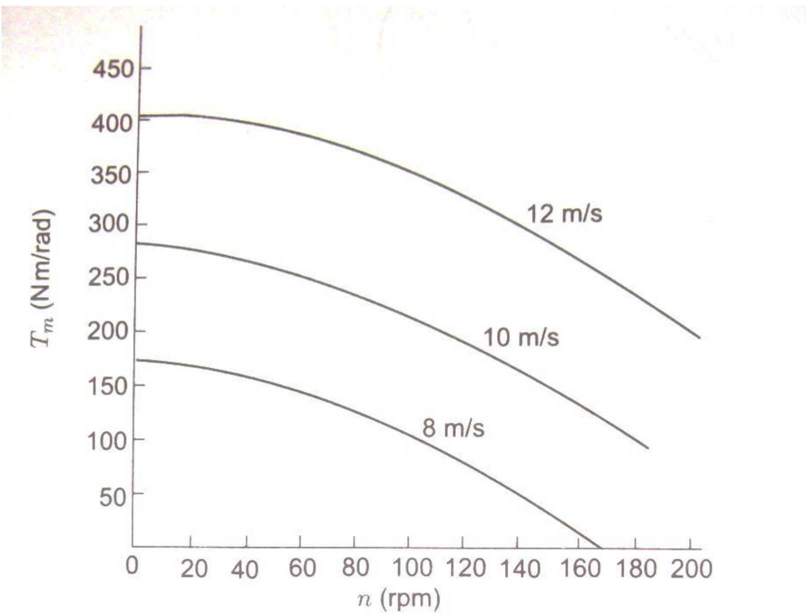
$$T_m = 0.5\ \rho\ C_{p,opt}\ \pi\ (R^5/\lambda_{opt}^3)\ \acute{\omega}^3.$$

Equation 2.14

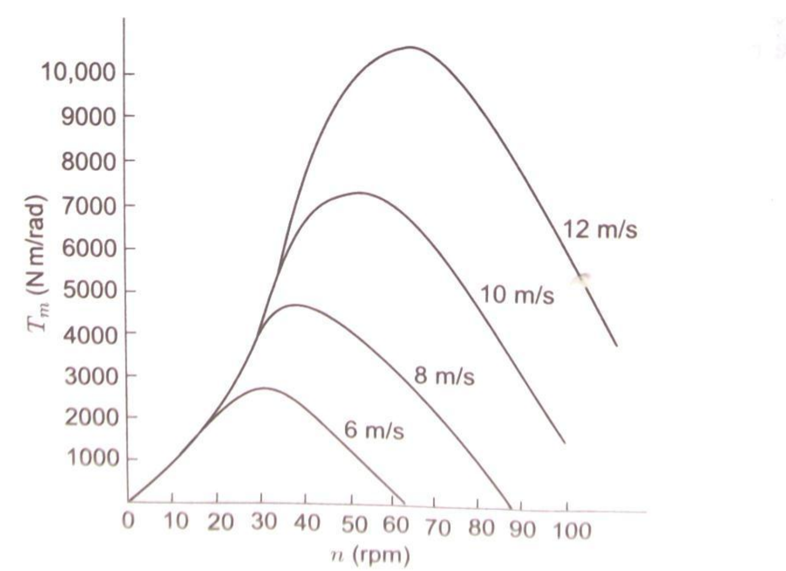
It is seen that at the optimum operating point on the C_p- λ curve, the torque is quadratically related to the rotational speed.

The torque speed characteristic curve shows that for the propeller turbine and the darrieus rotor, for any wind speed, the torque reaches a maximum value at a specific rotational speed, and this maximum shaft torque varies approximately as the square of the rotational speed. In case of electricity production, the load torque depends on the electrical loading, and by properly choosing the load (or power electronics interface), the torque can be made to vary as the square of the rotational speed.

The choice of constant of proportionality of the load is very important. At the optimal value, the Load curve follows the maximum shaft power. But a higher value, the load torque may exceed the turbine torque for most speeds.



(a)



(b)

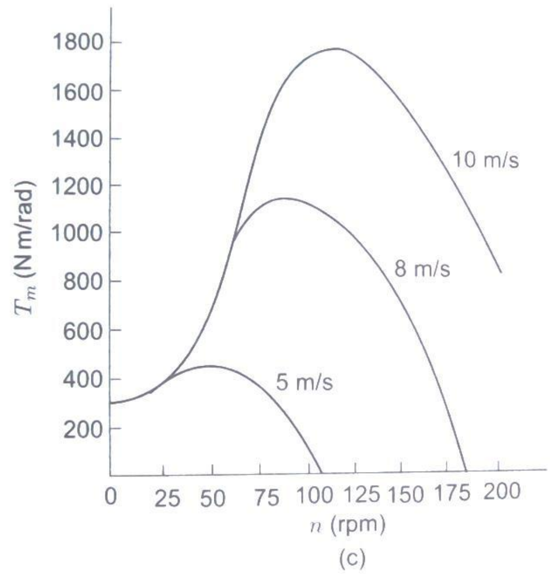


Figure 2.7 The Torque Speed Characteristics of Various Wind Machines: a. savonious rotor; b. Darrieus rotor; c. two-blade propeller-type

Consequently, a machine would fail to speed up above a very low value. If the constant k is lower than the optimal value, the machine may overspeed at the rated wind speed, activating the speed-limiting mechanism. Thus the proportionality constant of the load needs to be selected from a rather narrow range, about 10 -20 % of the optimum power curve. Note that the point of maximum torque is not the same as that of the maximum power.

As the power output is product of torque and speed, it also has the maxima that vary as the cube of the rotational speed. The matching characteristics of the load can make the load curve pass through the maximum power points at all the wind speeds. For generators that feed power to the grid, the torque- speed characteristics are tuned using power controls.

In terms of the power coefficient C_p, the aerodynamic torque becomes

$$\boldsymbol{T_m = 0.5\ \rho\ C_T\ \pi\ R^3\ V_\infty^3}$$

Equation 2.15

Where $C_T = C_p/\boldsymbol{\lambda}$ is called the torque coefficient.

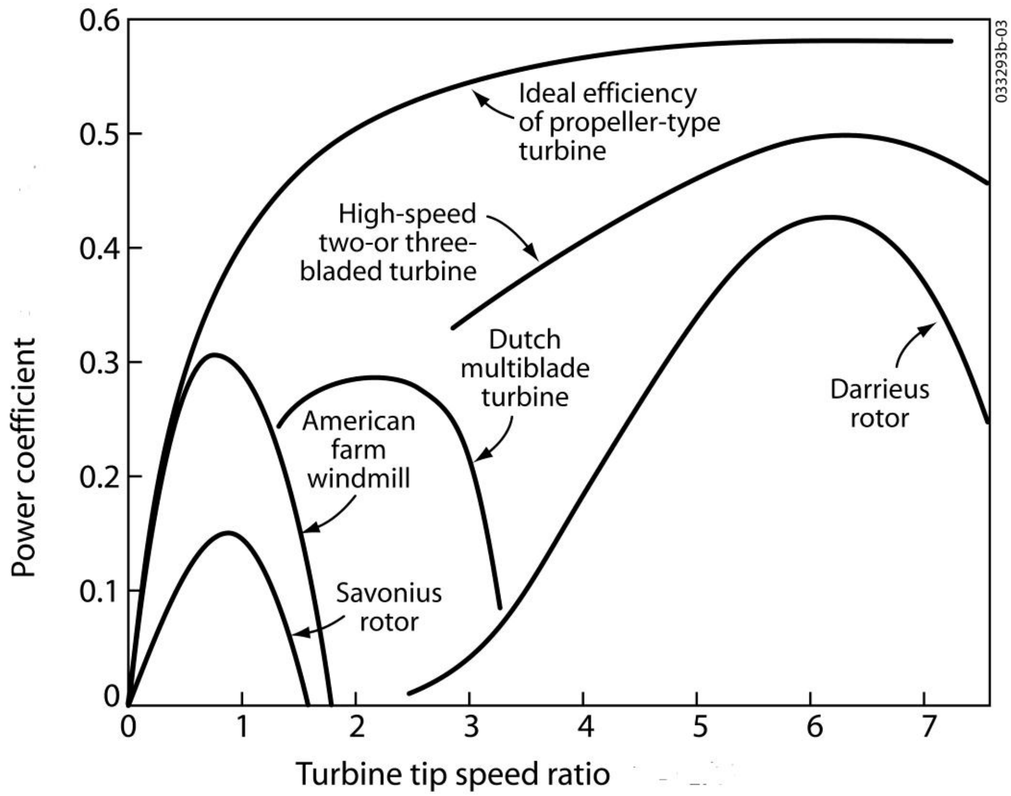


Figure 2.8 – Power coefficient versus turbine tip speed ratio

CHAPTER 3

Wind Turbine Control Systems

Wind turbines require certain control systems. Horizontal-axis turbines have to be oriented to face the wind. In high winds, it is desirable to reduce the drive train loads and protect the generator and the power electronic equipment for overloading, by limiting the turbine power to the rated value up to the furling speed. At gust speeds, the machine has to be stalled. At low and moderate wind speeds, the aim should be to capture power as efficiently as possible.

Along with many operating characteristics, the technical data sheet of a turbine mentions its output at a particular wind speed. This is the minimum wind speed at which the turbine produces its designated output power. For most turbines, this speed is normally between 9 and 16 m/s. The choice of the rated wind speed depends on the factors related to the wind characteristics of a given site. The generator rating is best chosen so as to best utilize the mechanical output of the turbine at the rated wind speed.

Wind turbines can have four different types of control mechanisms, as discussed below:

3.1 Pitch Angle Control:

The system changes the pitch angle of the blades according to the variation of wind speed. As discussed earlier, with pitch control, it is possible to achieve a high efficiency by continuously aligning the blade in the direction of the relative wind.

On a pitch controlled machine, as the wind speed exceeds its rated speed, the blades are gradually turned about the longitudinal axis and out of the wind to increase the pitch angle. This reduces the aerodynamic efficiency of the rotor, and the rotor output power decreases. When the wind speed exceeds the safe limit for the system, the pitch angle is so changed that the power output reduces to zero and the machine shifts to the ‘stall’ mode. After the gust passes, the pitch angle is reset to the normal position and the turbine is restarted. At normal wind speeds, the blade pitch angle should ideally settle to a value at which the output power equals the rated power.

The input variable to the pitch controller is the error signal arising from the difference between the output electrical power and the reference power. The pitch controller operates the blade actuator to alter the pitch angle. During operation below the rated speed, the control system endeavours to the pitch the blade at an angle that maximises the rotor efficiency. The generator must be able to absorb the mechanical power output and deliver to the load. Hence, the generator output power needs to be simultaneously adjusted.

3.2 Stall Control:

Passive stall control:

Generally, stall control to limit the power output at high winds is applied to constant-pitch turbines driving induction generators connected to the network. The rotor speed is fixed by the network, allowing only 1-4% variation. As the wind speed increases, the angle of attack also increases for a blade running at a near constant speed. Beyond a particular angle of attack, the lift force decreases, causing the rotor efficiency to drop. This lift force can be further reduced to restrict the power output at high winds by properly shaping the rotor blade profile to create turbulence on the rotor blade side not facing the wind.

Active stall control:

In this method of control, at high wind speeds, the blade is rotated by a few degrees in the direction opposite to that in a pitch controlled machine. This increases the angle of attack, which can be controlled to keep the output power at its rated value at all high wind speeds below the furling speed. A passive controlled machine shows a drop in power at high winds. The action of active stall control is sometimes called *deep stall*. Owing to economic reasons, active pitch control is generally used only with high-capacity machines.

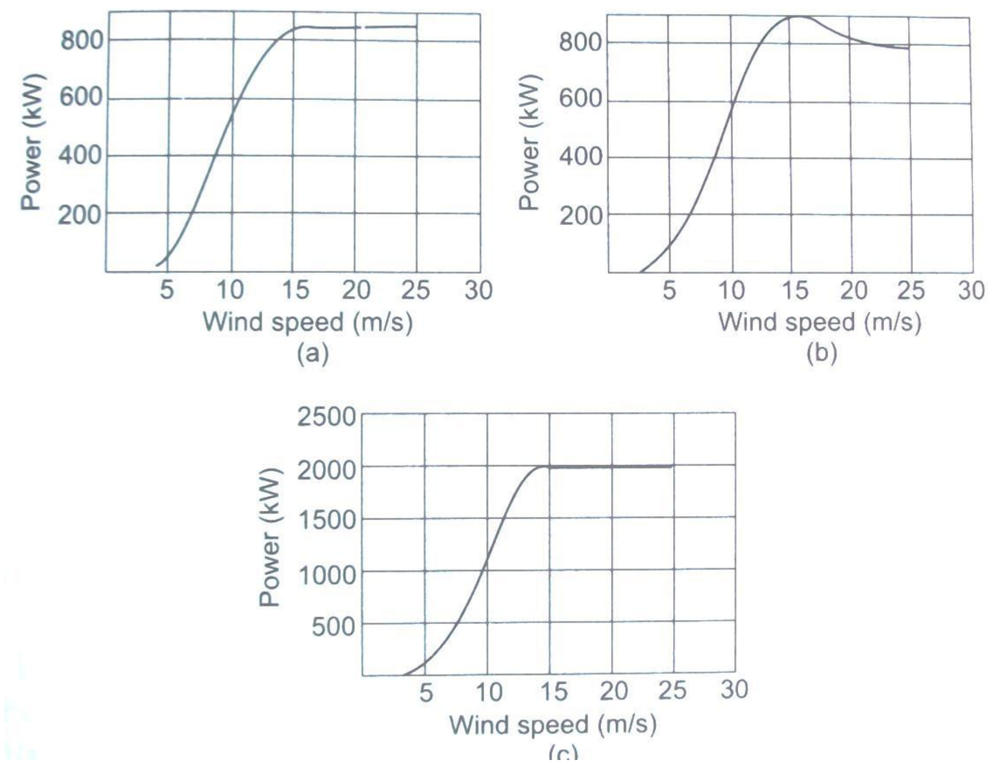


Figure 3.1 - Typical power profiles a.) pitch control b.) passive stall control c.) Active stall control

3.3 Power Electronic Control:

In a system incorporating a power electronic interface between the generator and load (or the grid), the electrical power delivered by the generated to the load can be dynamically controlled. The instantaneous difference between mechanical power and electrical power changes the rotor speed following the equation

$$J\frac{d\omega}{dt} = \frac{P_m - P_e}{\omega}$$

Equation 3.1

Where J is the polar moment of inertia of the rotor, ω is the angular speed of the rotor, P_m is the mechanical power produced by the turbine, and P_e is the electrical power delivered to the load.Integrating, we the above equation, we get

$$\frac{1}{2}J\left(\omega_2{}^2 - \omega_1{}^2\right) = \int_{t_1}^{t_2} (P_m - P_e)\, dt$$

Equation 3.2

Advantages of Power Electronic Control:

- Operation is smooth
- No mechanical action is involved.

Disadvantage of Power Electronic Control:

- Fast variation of speed requires a large difference between the input power and output power, which scales as the moment of inertia of the rotor resulting in a large torque and hence increased stress on the blades.
- Continuous control of rotor speed implies continuous fluctuation of the power output to the grid, which is usually undesirable for the power system.

3.4 Yaw Control:

Turbine is continuously oriented along the direction of the wind flow. This is achieved with a tail-vane in small turbines, using motorized control systems activated either by fan-tail, in case of wind farms, by a centralized instrument for the detection of the wind direction. It is also possible to achieve yaw control without any additional mechanism, simply by mounting the turbine downwind so that the thrust force automatically pushes the turbine in the direction of the wind.

Speed of the rotor can also be controlled using the yaw control mechanism. The rotor is made to face away from the wind direction at high wind speeds, thereby reducing the mechanical power. Yawing often produces loud noise, and it is restriction of the yawing rate in large machines to reduce noise is required.

3.5 Control Strategy:

Different speed control strategies are required for the five different ranges of wind speed.

- Power is not generated by the machine below a cut-in speed. Rotation of the machine may start in this speed range if there is sufficient starting torque. But no power is generated and rotor rotates freely.
- Maximum power is extracted from the wind at normal wind speeds. This is achieved at a particular TSR value. Hence, for tracking maximum power point, rotational speed is changed continuously proportional to the wind speed.
- At high wind speeds, rotor speed is limited to a maximum value which depends on the design of the mechanical components. Here C_p is lower than the maximum value. Power output is not proportional to the cube of the wind speed.
- At even higher wind speeds, output power is kept constant at the maximum value allowed by the electrical components.
- At cut-out or furling wind speed, the power generation is shut down and the rotation is stopped in order to protect the system components.

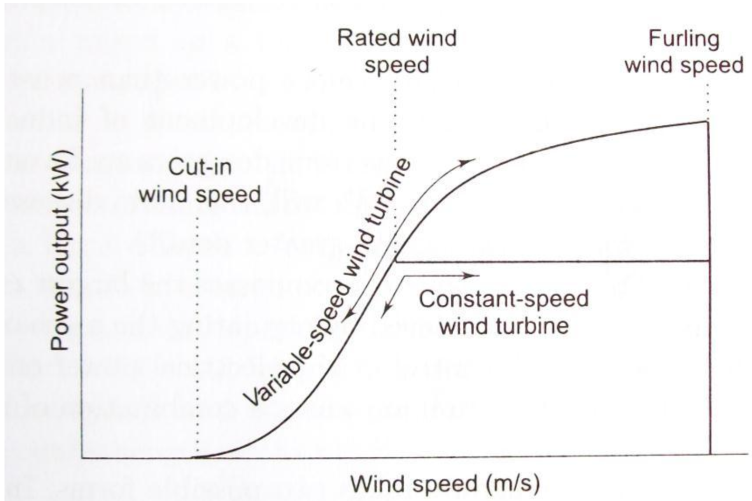


Figure 3.2 – Power versus wind speed characteristics of variable speed wind turbines

In the intermediate speed-range, the control strategy depends on the type of electrical power generating system used, and can be divided into two basic categories:

a) Constant speed generation scheme, and
b) Variable-speed generation scheme.

If the electrical system involves a grid-connected synchronous generator, the constant generation scheme is necessary. In the case of grid-connected squirrel cage induction generators, the allowable range of speed variation is very small, requiring an almost constant rotational speed.

But the constant-speed generation systems cannot maximise the power extraction from wind. Power coefficient reaches a maximum specific value of TSR for every type of wind turbine. Hence for the extraction of maximum power from wind, the turbine should operate at a constant TSR, which means the rotational speed should be proportional to the wind speed. So maximum power extraction requires a variable-speed generation system with the speed control for keeping a constant TSR.

Such systems can yield 20-30% more power than constant-speed generation systems. With the development of induction generators and power electronic converters, variable-speed generation systems are favoured.

The constant-TSR region is achieved by regulating the mechanical power input through pitch control or the electrical power output by the power electronic control. In many cases a combination of both is employed.

The control scheme can have two possible forms. In the first case, the value of the TSR for maximum C_p is stored in a microprocessor. The operating TSR is obtained from the measured values of the wind speed and rotational speed. An error signal is generated whenever the operating TSR deviates from the optimum TSR. If the current value of the TSR is greater than the optimum TSR, the power electronic converter increases the power output so that the rotational speed is reduced to the desired value. The opposite action is performed if the optimal value exceeds the current TSR.

This scheme has a few disadvantages. First, the wind speed measured in the neighbourhood of a wind turbine (or a wind farm) is not reliable indicator of V_∞ because of the shadowing effects. Also it is difficult to determine the value of TSR for maximum C_p. This value changes during the lifetime of a wind turbine due to the changes in the reference setting.

A second control scheme is devised to continuously track the maximum power point (MPP) using the property that the C_p versus TSR curve has a single smooth maximum point. This means that if operate at the maximum power point, small fluctuations in the rotational speed do not significantly change the power output. To implement this scheme, the speed is varied in small steps, the power output is measured and, and $\Delta P/\Delta\omega$ is evaluated. If this ratio is positive, more mechanical power can be obtained by increasing the speed. Hence the electrical power output is decreased temporarily by the power electronic control so that the speed increases. This increases the mechanical power, and can be obtained by increasing the speed. Hence the electrical power output is decreased temporarily by power electronic control so that the speed increases. This increases the mechanical power, and the electrical power, and the electrical power output is decreased temporarily by the power electronic control so that the speed increases. This increases the mechanical power, and the electrical power is again raised to a higher value. The process continues until the optimum speed is reached, when the mechanical power becomes intensive to speed fluctuations. When the wind speed changes, this mechanism readjusts the speed at the optimum value.

While controlling the rotational speed, it should be remembered that a large difference between mechanical power and electrical power results in a large torque and, hence, a large stress on the rotor components. It is necessary to limit the acceleration and deceleration rates to values dictated by the structural strength of mechanical parts.

.

CHAPTER 4

GRID CONNECTED AND SELF EXCITED INDUCTION GENERATOR

Induction Generators for Wind Energy Conversion Systems:

4.1 Constant Voltage, Constant frequency Generation (Line excited Induction Generator):

These derive its excitations from the utility bus. It is also called line excitation. Rotor is driven by the prime mover at super synchronous speeds. Generator draws lagging VAr from the bus and feed real power to the supply system. The cage rotor induction generators feed only through the stator and operate at low negative slip. Wound induction generators can feed power through the stator as well as rotor and operate over a wide speed range.

4.2 Reactive Power and Harmonics:

The grid connected induction generator draws its excitation from the power line to setup its rotating magnetic field and demands lagging reactive power. Such reactive power given may adversely affect the voltage level particularly in weak public utility networks and increases system losses. For large wind turbines driving induction generators, the voltage fluctuation and flickering arising from power output variation may exceed the saturation limit of the utility system.

This lagging reactive power is drawn from the supply through stator, thus reducing KW output for same current loading. If the rotor side converter is force commutated or uses IGBTs or BJTs, it can meet the reactive power demand. If firing angle is made > 180_o for sub synchronous speed operation. Thus it generates the leading VAr. Firing angle of Converter2 is always < 180_o and for that reason it draws leading VAr from supply through the transformer. However force commutation of IGBT, unity or lagging p.f operation is possible and overall p.f of the system can be improved.

In the residual converter, SCR with 120° mode of conduction are used. They inject low order harmonics into the supply system. Converter1 also injects low order and turbine current harmonics to mmf waves. Using PWM Technique with both the converters harmonics spectrum is shifted form low order to high order which can be easily filtered with PWM converters. AC line current can be made to quasi sinusoidal with appropriate phase shift related to supply voltage. Thus p.f is improved and harmonics are eliminated.

The smoothing reactor in the dc link reduces the ripple in DC link current. However it is expensive and makes the system bulkier.

The other option is to use a capacitor across the dc link instead of an inductor. IT reduces ripples in dc link voltage making it steady dc. When Converters 1 & 2 are PWM voltage fed type and use IGBTs following characteristics can be obtained.

4.3 Reactive Power Compensation:

In double output induction generators with slip power control, the reactive power demand of generators is generated by converter 1. Its firing angle is made > 180^{o} for sub synchronous speeds and < 360^{o} for super synchronous speeds. Thus converter acts like a variable capacitor providing the VAr requirement of Induction generator while transferring the real power to utility grid via dc link. However in squirrel cage induction generators, the reactive power demand is made by a bank of capacitors or other VAr compensators. VAr compensators improve voltage stability, increase network capability and decrease losses. Various types of VAr compensators are Thyristor controlled reactor, static VAr compensator.

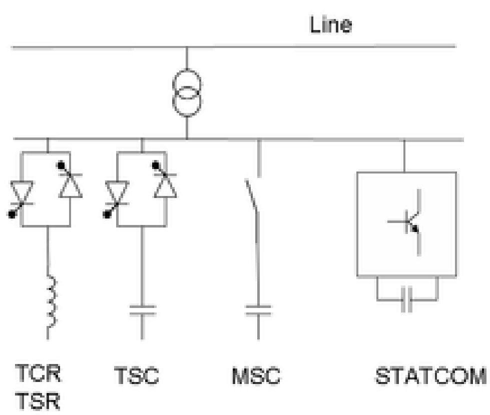


Figure 4.1 – Various Devices used for reactive power compensation

1. **Thyristor switched capacitors:**

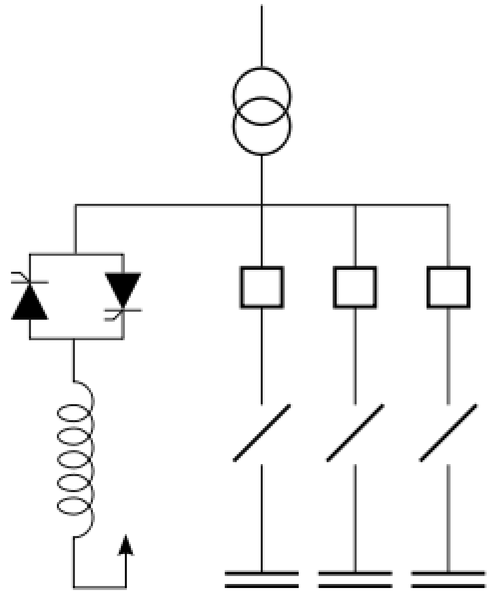


Figure 4.2 Thyristor Switched Capacitor

A bank of capacitors are switched ON and OFF in response to pre-set voltage levels. Contractors used in old systems for switching are replaced by thyristors for faster control. Continuous control of VAr is not possible with TSC as capacitor would remain in the circuit for full cycle before thyristor switches off when current limiting reactors are used in series with capacitors to limit the current that may arise due to the difference between the supply and capacitor voltages at the switching ON instant. In a 3 phase system, capacitor banks are delta connected to avoid triple n harmonics in line currents.

2. **Thyristor Controlled Reactor:**

The disadvantage of thyristor switched capacitor is discontinuous control of VAr is eliminated using Thyristor controlled reactor. Fixed capacitor bank rated at full load VAr demand of the induction generator is connected in parallel with the line variable VAr is realized by varying the firing angle between 90_o and 180_o. The excess reactive power from the capacitor bank at reduced load is absorbed by the inductor when delay angle approaches 90_o. TCRs in a 3 phase system are Δ connected to avoid triple n harmonics in compensating line currents.

3. **Static VAr compensator:**

It is the recent trend in reactive power control using voltage source PWM inverters. IT is the static realization of the synchronous condenser. Inductors are connected in series with AC supply. The inverters generate or absorb reactive power depending on its AC output voltage which in turn controlled to witching of IGBTs. The inverter produces a set of balanced voltages at the output terminals whose fundamental component VR is in phase with corresponding AC system voltage V_s. So only reactive power flows between the converter and system. When inverter output voltage VR is greater than AC system voltage VS, inverter acts as a capacitor generating lagging VAr. If $V_R < V_S$ inverter acts as an inductor absorbing lagging VAr. In a practical inverter to supply inverter losses, the inverter output voltage VR is made to lag behind AC system voltage in case of capacitor operation and lead the AC system Voltage in case of inductor operation.

Function of dc link capacitor is to eliminate or reduce the ripples in dc link voltage.

STATCOM:

A **STATCOM** or Static Synchronous Compensator is a regulating device used on alternating current electricity transmission networks. It is based on a power electronics voltage-source converter and can act as either a source or sink of reactive AC power to an electricity network. If connected to a source of power it can also provide active AC power.

A **STATCOM** works by rebuilding the incoming voltage waveform by switching back and forth from reactive to capacitive load. If it is reactive, it will supply reactive AC power. If it is capacitive, it will absorb reactive AC power. This is how it acts as a source/sink.

Uses:

Usually a STATCOM is installed to support electricity networks that have a poor power factor and often poor voltage regulation. There are a number of other uses for STATCOM devices including, wind energy voltage stabilisation, and harmonic filtering. However, the most common use is for voltage stability.

4.4 Induction Generator versus Synchronous Generator:

Synchronous generators and induction generators have their own merits and limitations. The balance between the advantages and disadvantages of the two is situation specific. A cage induction machine is preferred for its ruggedness and low cost compared to a synchronous generator.

The induction machine, coupled to the utility system, finds favour for fixed-pitch, nearly constant speed wind turbines in order to provide damping for the wind turbine drive train when it faces fluctuation in the power input due to wind speed variations. An induction generator has no synchronization problem. It has relaxed stability criteria and is practically free form hunting owing to the presence of damping, given by the slope of the induction machine torque-slip curve. On the other hand, transient stability may be a serious problem with the grid-connected synchronous machine as it represents a stiff compliance in the dynamic model of the wind turbine drive train. Damping must be provided for either in the machine or mechanically in the drive train.

For symmetrical faults, an induction generator does not contribute any fault current to the network except instantaneous fault current, while for unbalanced faults the contribution is sustained. Whether it is balanced or unbalanced fault, a synchronous generator contributes fault current.

An induction generator demands lagging reactive VA of the order of 30% of its output kVA from the utility system and produces a current surge at the time of witching-in and during acceleration, both these adversely affecting the voltage of a network with a low fault level. Against this background, a synchronous generator has a low excitation demand, and its active and reactive power can be adjusted by pitch control and field control. In autonomous systems, voltage adjustment by field control is simple.

4.5 Effect of wind generator on the Network:

Wind power injected into the network affects the voltage magnitude, its flicker, and its waveform at the *point of common coupling* (PCC).

The effect on voltage magnitude depends on the strength of the utility distribution network at the point of coupling as well as on the active and reactive power of the wind generator(s). The system strength at the PCC under consideration is decided by the short-circuit power, called the *fault level* at that point. The short circuit power is the product of short circuit current, following a three-phase fault at that point and the voltage of the system. In fact, a power system comprises many interconnected power sources. The loads are fed through extended transmission and distribution networks. At the point of connection, an equivalent ideal voltage source in series with impedance Z_s may be assumed to replace the power system. Thus, the higher the fault current, the lower is the source impedance. The wind farm with induction generators receives the reactive power from the network and delivers real power to it. Without contribution from the wind generator, the fault level at the point of connection near the wind farm is

$$\boldsymbol{M = I_f V_s}$$

Where

$$\boldsymbol{I_f = V_s/Z_s}$$

Equation 4.2

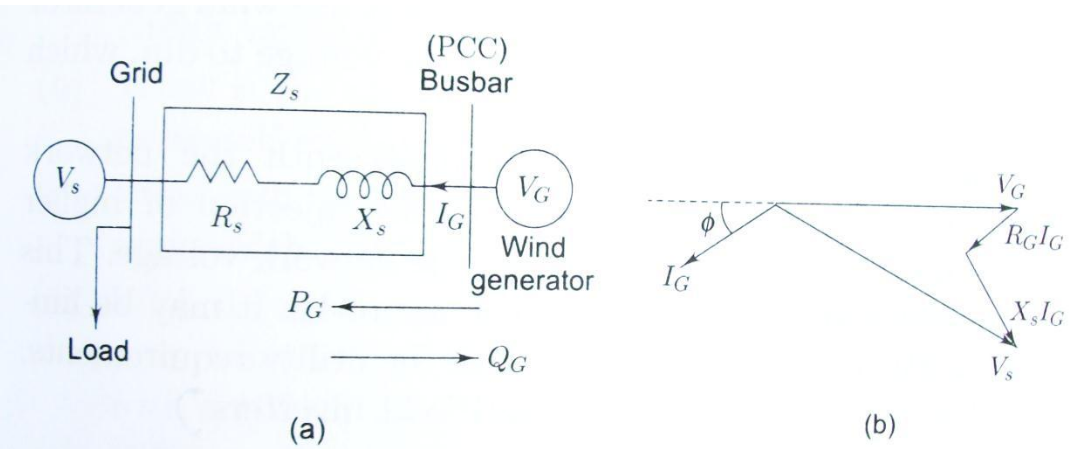


Figure 4.3 – a. Schematic diagram of generator connection and distribution

b. phasor diagram

Thus the fault level and hence the network strength are indicative of the source impedance. Areas of high wind velocity are suitable locations for wind farms. These areas are usually sparsely populated. Long transmission and distribution lines are normally required for connecting wind farms with the power system network. As a result, fault levels at the wind farms are generally low, making them weak electrical systems.

If the phase difference between V_s and V_G is not large, the voltage at the PCC will be close to

$$V_G = V_s + R_s I_G cos\phi - X_s I_G sin\phi$$

$$V_G = V_s + \frac{P_G R_s}{V_G} + \frac{Q_G X_s}{V_G}$$

Equation 4.3

At low power delivery, the voltage at the PCC reduces if the induction generator absorbs reactive power from the grid, while, at increased power flow, the voltage rises.

Flicker:

Flicker is defined as the unsteadiness of the distribution network voltage. It may be caused by the continuous operation of a wind turbine or switching operation of turbines. While operating, the rotor of a wind turbine experiences a cyclic torque variation at the frequency with the blades move past the tower. The cyclic power variation may lead to flicker, and depends on the wind speed distribution at the site. While being connected to the network, the induction generator draws excessive current. Soft-start systems are usually employed to minimize the transient inrush current. However at very high wind speeds, sudden disconnection of the wind generator from the distribution network may cause the voltage to dip, which cannot be avoided.

4.6 DOUBLY FED INDUCTION GENERATOR

1. In a doubly fed induction machine, two windings participate in energy conversion process. They can work at double the synchronous speed for constant torque, similar to synchronous machine but in synchronous machine only one winding participate in energy conversion DFIM (doubly fed induction machine) is to operate in narrow speed ranges.

2. **CONSTRUCTION**

1. Wound Rotor DFIM.
2. Brushless wound rotor:
   a. Brushless DF Induction electric machine.
   b. Brushless wound rotor DF electric machine.

Wound rotor DFIM uses the two windings of same power rating. One is winding on stator and the other on rotor. Stator supply is Normal 3 phase supply. Rotor supply is from power frequency converter. Slip ring assembly used to transfer Power to rotor winding. In a brushless DFIM **t**wo windings are adjacent to each the other on stator. Windings are excited separately. Brushless wound rotor DFIM **is s**imilar to wound rotor DFIM but slip ring assembly is not used. It has a large efficiency and less cost but instability is more.

WORKING:

Field can be from rotor or stator or from both. Both active power (for torque) and reactive power (for flux) have to be fed to rotor**.** Multi-phase supply with frequency f is given to stator. Control Frequency converter converts power from supply frequency to slip frequency.

ADVANTAGES:

- Theoretically system cost is half of other machines with same rating.
- Higher efficiency can be achieved due to less loss.
- Rotor core is effectively utilized hence power density is large.
- Active and reactive power to grid can be controlled using electronic converters.
- DFIG can work in variable speed range around synchronous speed.

DISADVANTAGES:

- The wound rotor type is not reliable due to slip ring assembly.
- Brushless DFIM has less efficiency and high cost.

APPLICATIONS:

- DFIG kept synchronized with grid uses wind source more effectively.
- High power pumps and fans.
- Used in hydro generators.
- Used in ships…etc.

CONCLUSION:

Wound rotor DFIM found commercial success in very large applications with limited speed range. For a low cost, highly efficient and reliable electronic controlled DFIM is kept under study

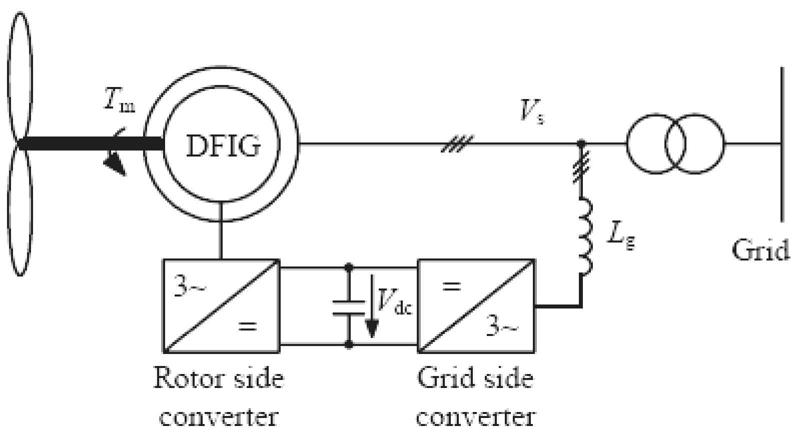


Figure 4.4 – DFIG Connected to the Grid

CHAPTER 5

SIMULATIONS

1. **Pitch Control – analysis by MATLAB**

Explanation:

$$P_m = 0.5\ C_p\ (\boldsymbol{\lambda}, \beta)\ \rho A V_w^3$$

Equation 5.1

Where

P_m is the Mechanical output power of the wind turbine;

C_p ($\boldsymbol{\lambda}$,α) is the performance coefficient of the turbine;

ρ is the density of air in kg/m^3;

A is the turbine swept area in m^2;

V_w is the speed of wind (m/s);

$\boldsymbol{\lambda}$ is the tip speed ratio;

β blade pitch angle (degrees)

A generic equation is used to model C_p ($\boldsymbol{\lambda}$,β) :

$$C_p(\boldsymbol{\lambda},\beta) = C_1(\frac{C_2}{\lambda} - C_3\beta - C_4)e^{\frac{-c_5}{\beta}} + C_6\boldsymbol{\lambda}$$

Equation 5.2

Where

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

Equation 5.3

The coefficients c_1 to c_6 are: c_1 = 0.5176, c_2 = 116, c_3 = 0.4, c_4 = 5, c_5 = 21 and c_6 = 0.0068. The C_p-λ characteristics, for different values of the pitch angle β, are illustrated below. The maximum value of C_p (C_{pmax} = 0.48) is achieved for β = 0 degree and for λ = 8.1. This particular value of λ is defined as the nominal value ($\lambda_{\_nom}$).

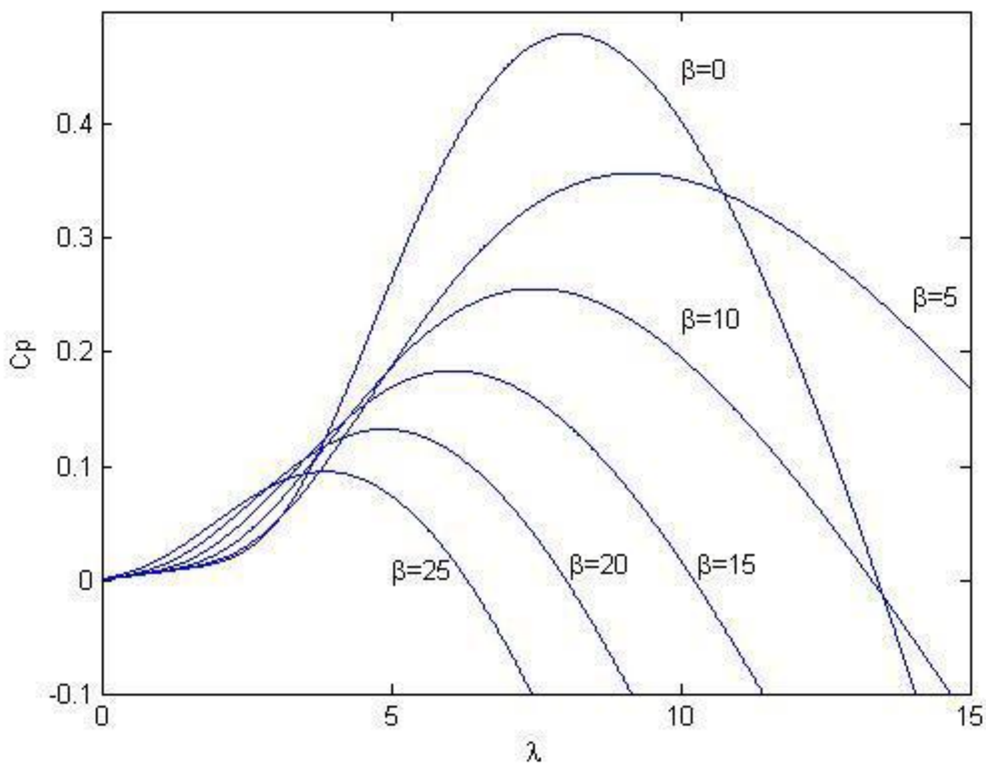


Figure 5.1 Power coefficient versus tip speed ratio

From the above graph we can see that we can obtain a maximum value of cp for a particular value of TSR. Based on this idea, the following algorithm was developed which calculates the value of pitch angle for getting the maximum value of C_p for a particular TSR.

We calculate TSR (tip speed ratio) in a case where the blade tip speed is almost constant in the case of a fixed speed turbine. And a C_p- $\boldsymbol{\lambda}$ graph is calculated for different values of beta (pitch angle).

TSR = tip of blade/ wind speed

OR

$$\boldsymbol{\lambda} = 2\Pi RN / V_{\infty}$$

Equation 5.4

MATLAB CODE:

```
%meshgrid(tsr,pitch);

Cp=0;

c1=0.5176;

c2=116;

c3=0.4;

c4=5;

c5=21;

c6=0.0068;

n=size(tsr);

for i=1:6

for j=1:n(2)

tsr_i=(1/(tsr(j)+0.08*pitch(i))-0.035/(pitch(i)^3+1))^(-1);

Cp(j)=c1*(c2/tsr_i-c3*pitch(i)-c4)*exp(-c5/tsr_i)+c6*tsr(j);

end

plot(tsr,Cp);

hold on;

end

axis ([0 15 -0.1 0.5 ]);

xlabel('\lambda'),ylabel('Cp');
```

2. Turbine Characteristics :analysis by MATLAB

Both horizontal and vertical axis wind turbines are used in wind generation systems. The vertical darrieus (egg beater) type has the advantages that it is located on the ground, can accept wind from any direction without any special yaw mechanism and, therefore, it is preferred for high power output. The disadvantages are that the turbine is not self-starting and there is a large pulsating torque which depends on wind velocity, turbine speed, and other factors related to the design of the turbine. The aerodynamic torque of a vertical turbine is given by the equation

$$T_m = C_p(\lambda) . [0.5\frac{\rho\pi R_\omega^3}{\eta_{Gear}}] . V_\omega^2$$

Equation 5.5

Where

$\boldsymbol{C_p}$= power coefficient

$\boldsymbol{\lambda}$ = tip speed ratio (TSR)

$\boldsymbol{\rho}$ = air density

$\boldsymbol{R_W}$, = turbine radius

$\boldsymbol{\eta_{gear}}$= speed-up gear ratio v, = wind velocity

$\boldsymbol{V_w}$= turbine angular speed

$\boldsymbol{W_w}$=turbine angular speed

The power coefficient (C,) is the figure of-merit and is defined as the ratio of actual power delivered to the free stream power flowing through a similar but uninterrupted area, and tip speed ratio (TSR) is the ratio of turbine speed at the tip of a blade to the free stream wind speed. The oscillatory torque of the turbine is more dominant at the first, second, and fourth harmonics of fundamental turbine angular velocity and is given by the expression

T_{osc}= T_m . [A cos($\acute{\omega}_w$)+B cos($\acute{\omega}_w$) +C cos($\acute{\omega}_w$)]

Equation 5.6

Where A, B, and C are constants. **Fig. 3** shows the block diagram of the turbine model with oscillatory torque. A typical family of turbine torque speed curves at different wind velocities is shown in Figure

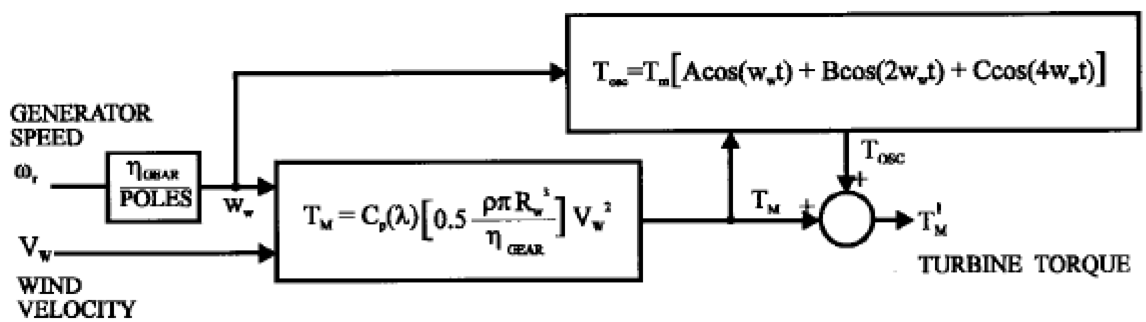


Figure 5.2 – Model of a wind turbine with oscillatory torque

%torque speed characteristic of a wind turbine

density=2.25;

Rw=20;

Gear_ratio=5;

Cp=0.25;

Vw=[6 6.5 7];

for i=1:3

```
Tm(i)=Cp*((0.5*density*pi*Rw^3)/(Gear_ratio))*Vw(i)^2;

end


%computed the aerodynamic torque of the vertical turbine


A=0.015;

B=0.03;

C=0.015;


t=1;


rotor_speed=linspace(-4,-2,100);

Tosc=Tm(1)*(A*cos(rotor_speed*t)+B*cos(2*rotor_speed*t)+C*cos(4*rotor_speed*t));

%computed the oscillatory torque.

Tm1=Tosc+Tm(1);

plot(rotor_speed,Tm1);

hold on;


rotor_speed=linspace(-1,1,100);

Tosc=Tm(2)*(A*cos(rotor_speed*t)+B*cos(2*rotor_speed*t)+C*cos(4*rotor_speed*t));

%computed the oscillatory torque.

Tm1=Tosc+Tm(2);

plot(rotor_speed,Tm1);
```

```
hold on;

rotor_speed=linspace(2.2,4.2,100);

Tosc=Tm(3)*(A*cos(rotor_speed*t)+B*cos(2*rotor_speed*t)+C*cos(4*rotor_speed*t));

%computed the oscillatory torque.

Tm1=Tosc+Tm(3);

plot(rotor_speed,Tm1);
```

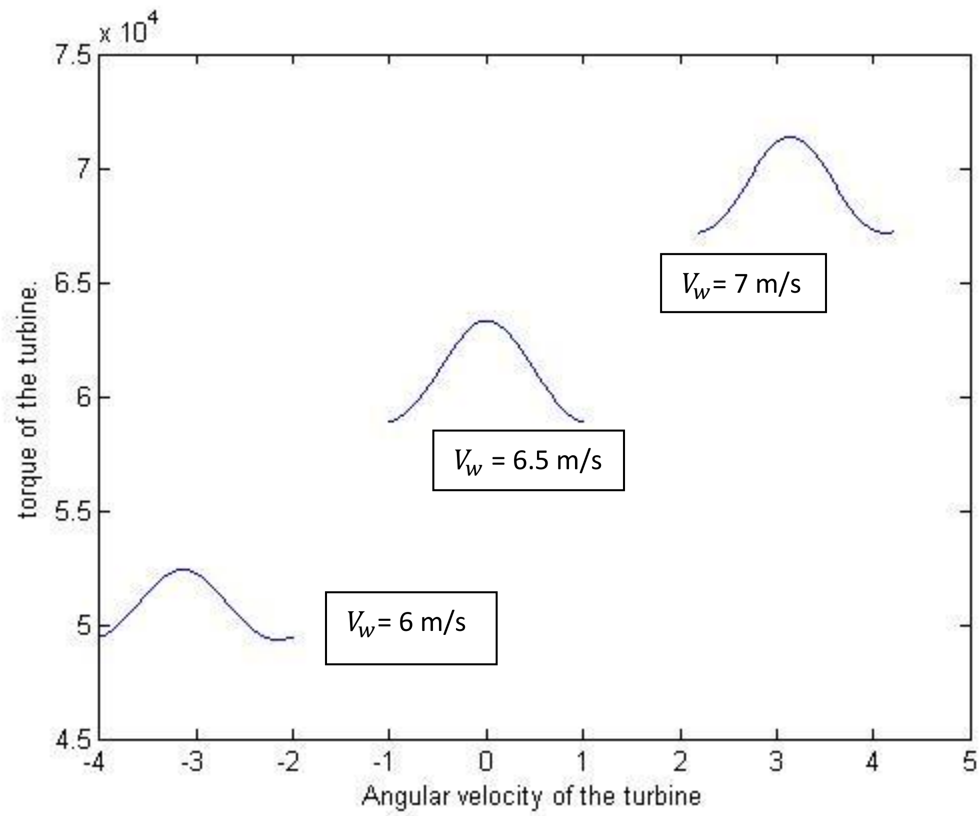


Figure 5.3 Torque-speed characteristics of wind turbine at different wind speeds.

References:

I. India wind energy outlook 2009

II. Alternative energy systems , design and analysis with induction generators by m. Godoy simones and felix a. farret.

III. http://www.seminarprojects.com/Thread-doubly-fed-induction-motor-full-report#ixzz14v8lm52E

IV. Renewable and Efficient electric power systems by Gilbert. M .Masters, Wiley Interscience

V. Intelligent Control of a Variable Speed Cage Machine Wind Generation SystemVOL. 12, NO. 1, JANUARY 1997Marcelo Godoy Simoes,, Bimal K. Bose,, and Ronald J. Spiegel.

VI. P. G. Casielles, J. G. Aleixandre, J. Sanz, and J. Pascual, “Design, installation and performance analysis of a control system for a wind turbine driven self-excited induction generator,” in Proc. ICEM ’90, Cambridge, MA, Aug. 1990.

VII. ‘Wind Electrical Systems by’ S.N Bhadra, D.Kastha, and S. Banarjee , Oxford University Press, 2005

VIII. “Wind as a renewable source of energy & torque speed characteristics of a wind turbine driven induction generator” by Abhisek Das, Saurav Mallick, Sushmee Badhulika, NIT Rourkela, 2007

IX. ‘Wind Power In Power Systems’ by Thomas Ackerman, John Wiley and Sons, 2005

X. Renewable energy from Wikipedia, the free encyclopaedia

XI. NWTC Wind Resource Information

XII. Ministry of Non-conventional Energy Sources(MNES) www.mnes.nic.in

XIII. http://www.mpoweruk.com/wind_power.htm