A STUDY OF WIND ENERGY POTENTIAL IN INDIA

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

Bachelor of Technology
In
Electrical Engineering

By

BIBEK SAMANTARAY & KAUSHIK PATNAIK

Department of Electrical Engineering
National Institute of Technology
Rourkela
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Under the guidance of
Prof. S.RAUTA

Department of Electrical Engineering
National Institute of Technology
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CERTIFICATE OF AUTHENTICITY

This is to certify that the project report titled "Study of Wind Energy in India" submitted by Bibek Samantaray, Roll No. 10602008 & Kaushik Patnaik, Roll No. 10602039, in fulfillment of the requirements for the final year B. Tech. project in Electrical Engineering Department of National Institute of Technology, Rourkela is an authentic work carried out by them under my supervision and guidance.

Date:

Prof. Sankarsan Rauta
Dept. of Electrical Engineering
National Institute of Technology
Rourkela- 769008

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Bibek Samantaray
10602008

Kaushik Patnaik
10602039

Abstract

There is huge activity in wind power, pan-India with the installed capacity increasing to 10,000 MW. India today has the fifth largest installed capacity of wind power in the world with 11087MW installed capacity and potential for on-shore capabilities of 65000MW. However the plant load factor (PLF) in wind power generation is very low, often in the single digits. The increase in interest in wind energy is due to investment subsidies, tax holidays, and government action towards renewable energy playing a big part in nation's energy system. There is a need to generate environment friendly power that not only raises energy efficiency and is sustainable too. The time has come for moving to generation based subsidies and understanding the drawbacks associated with wind power in India. The capital cost of wind power is third higher than conventional thermal power; further electrical problems like voltage flicker and variable frequency affect the implementation of wind farm. However advances in technologies such as offshore construction of wind turbines, advanced control methodologies, and simulation of wind energy affecting overall grid performance are making a case for wind energy.

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CHAPTER-1

INTRODUCTION

BACKGROUND

The wind turbine first came into being as a horizontal axis windmill for mechanical power generation, used since 1000 AD in Persia, Tibet and China. Transfer of mechanical windmill technology from the Middle East to Europe took place between 1100 and 1300, followed by further development of the technology in Europe. During the 19th century many tens of thousands of modem windmills with rotors of 25 meters in diameter were operated in France, Germany and the Netherlands, most of the mechanical power used in industry was based on wind energy. Further diffusion of mechanical windmill technology to the United States took place during the 19th Century.

The earliest recorded (traditional) windmill dates from the year 1191 at the Abbey of Bury St Edmunds in Suffolk. It replaced animal power for grinding grain and other farm activities like drawing water from well, the popularity of wind turbines increased tremendously and they soon dotted the landscape.

The advent of DC electric power in 1882, and introduction of 3-phase AC power production in the early 1890s, provided a technological basis for constructing wind turbines that generated electricity. The Danish scientist and engineer Poul La Cour is the most widely known pioneer of electricity generation using wind power. In 1891 in Askov, Denmark he introduced a four shuttle sail rotor design generating approximately 10kW of DC electric power. He also applied the DC current for water electrolysis, and utilized the hydrogen gas for gas lamps to light up the local school grounds. La Cour's efforts started research, development and commercialization of wind electricity in Europe and thus Europe gained its leadership role in wind energy electricity generation. Though less recognized than La Cour, Charles F. Brush in 1888 introduced in Cleveland Ohio the first automatically operating wind turbine generator, a 12kW, 17-meter-diameter machine, operated for 20 years.

By 1908 there were several wind mills in operation for electricity generation, with capacities ranging from 5-25 kW. By 1930’s wind turbines with capacity of 500kW were developed which found wide spread use in inaccessible areas. With concerns over climate change and depleting and polluting fossil fuels wind power has emerged as the most promising source of renewable energy:

Table 1: Historical Development of Wind Turbines

Date	Typical Capacity	Typical Blade Length	Typical Technology
Mid 1990s	400-500 kW	15-25 m	Fixed rotational speed and fixed blade pitch angle
2000	1000 kW	25-35 m	Dual rotational speed and fixed blade pitch angle
Today	2000-3000 kW	35-45 m	Variable rotational speed and variable blade pitch angle
Within 5 years	3000-7000 kW	45-60 m	

Today wind turbines are considered to be the most developed form of renewable energy technology, with industrial giants such as Siemens and GE amongst the leading manufacturers. In 2006, some 11,000 turbines were produced with a combined capacity of 16,000 MW and the global market was worth an estimated £13,000 million. Installed capacity is expected to pass 100 GW in 2008, the equivalent of 50-100 nuclear power stations.

Wind Energy

The energy that can be extracted from the wind is directly proportional to the cube of the wind speed, so an understanding of the characteristics of the wind (velocity, direction, variation) is critical to all aspects of wind energy generation, from the identification of suitable sites to predictions of the economic viability of wind farm projects to the design of wind turbines themselves, all is dependent on characteristic of wind. The most striking characteristic of the wind is its stochastic nature or randomness. The wind is highly variable, both geographically and temporally. Moreover this variability exists over a very wide range of scales, both in space and time. This is important because extractable energy from wind varies with the cube of wind velocity. This variability is due to different climatic conditions in the world also the tilt of earth on its axis and its own spinning results in different wind distributions across the world. Also within any climatic region, there is a great deal of variation on a smaller scale, which is dictated by several factors such as ratio of land and water, presence of mountains etc. The type of vegetation also affects wind distribution through absorption of moisture, temperature moderation and reflection of sun's energy. Generally more wind is witnessed on the tops of hills and mountains than in low level areas. Even more locally, wind velocities are altered by obstacles such as trees or buildings. For any location there is variation of wind pattern, wind speed may vary from year to year, also wind distribution will change from decade to decade. These long-term variations are not well understood, and thus make it difficult to make predictions of the economic viability of wind-farm projects. Wind distribution is more predictable over shorter time spans like a year, but on shorter time frame like few days the wind energy is difficult to predict. These variations are due to the weather systems. Depending on location, there may also be considerable variations with the time of day (diurnal variations), which are fairly predictable. These variations are important to be considered because they can affect production of large scale wind energy and consequent integration into grid, also associated power generation systems must be prepared for these variations. Also we must take into account the fact that short term turbulence cause variations in the quality of power delivered.

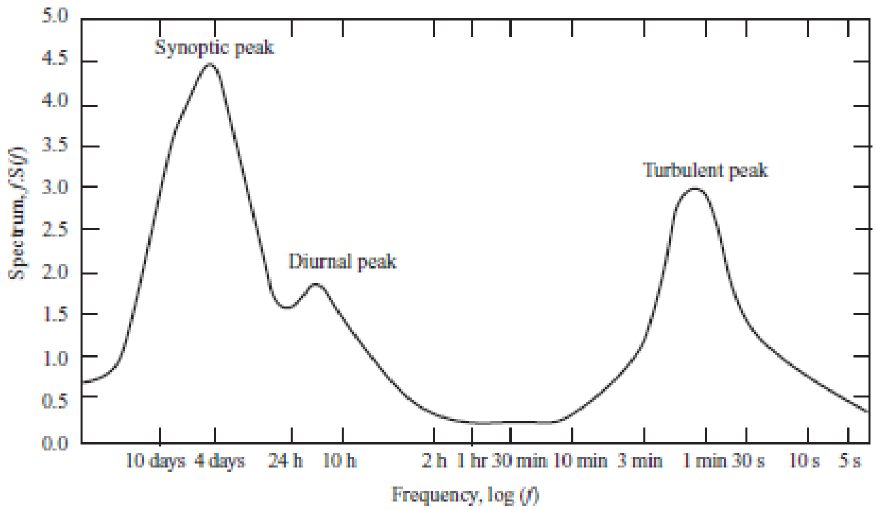


Figure 1 : Van der Hoven Wind Spectrum Curve

Van der Hoven (1957) created a wind-speed spectrum from long- and short-term records at Brookhaven, New York, showing clear peaks corresponding to the synoptic, diurnal and turbulent effects referred to above. The 'spectral gap' between the diurnal and turbulent peaks shows that these variations can be treated quite distinct from the higher-frequency fluctuations of turbulence.

Major factors that have accelerated the wind-power technology development are as follows:

1. Development of high-strength fiber composites for constructing large low-cost blades.
2. Reduction in prices of the power electronics components such as converters.
3. Variable-speed operation of electrical generators to capture maximum energy.
4. Improved plant operation, pushing the availability up to 95 percent.
5. Economy of scale, as the turbines and plants are getting larger in size.
6. Accumulated field experience (the learning curve effect) improving the capacity factor.

The total power generating capacity has grown to about 11087MW as of March 2010 thus placing India at fifth place in terms of installed capacity.

Power in a wind stream

A wind stream has total power given by **Pt = m. (K.E.w)** = 0.5**m.Vi^2**

Where, m = mass flow rate of air, kg/s

V_i = incoming wind velocity, m/s

Air mass flow rate is given by

$$\mathbf{m = \dot{\rho} A V_i}$$

Where, $\dot{\rho}$= Density of incoming wind, kg/m^2 = 1.226 kg/m^2 at 1 atm, 15^{o}C

A = Cross-sectional area of wind stream, m^2

Substituting the above and accounting for the constants, we arrive at the following:

$$\mathbf{P_W = 0.5\rho\pi R^3 V_w{}^3 CP(\lambda,\beta)}$$

Where,

Pw = extracted power from the wind,

ρ= air density, (approximately 1.2 kg/m3 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)

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

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

Betz Limit

Betz limit is the theoretical limit assigned to efficiency of a wind turbine. It states that no turbine can convert more than 59.3 % of wind kinetic energy into shaft mechanical energy. Thus the value of C_p is limited to Betz limit. For a well designed turbine the efficiency lies in the range of 35-45 %.

Capacity Factor

Capacity factor is a term used to denote the utilization rate of a wind turbine or any power generating source for that matter. It is the ratio between power produced to the power that could have been produced if the generation source operated at 100% efficiency.

Capacity Factor = Actual amount of power produced over time / Power that would have been produced if turbine operated at maximum output 100% of the time

A conventional plant utilizing fossil fuels will naturally have a larger capacity factor as it is a continuous process. If the plant is laid idle or under maintenance then only will the capacity factor drop down.

For a Wind turbine however it is more of a question of the availability of the wind, as the wind is random in speed and direction, therefore a wind turbine may not always operate at maximum output condition. Also there lies a cut-in and furl in speed which means the turbine only acts within a specific window. The capacity factor of turbines is typically low around 40 %.

Also, for a fuel powered plant capacity factor denotes the reliability of the plant, but in case of wind turbines it encompasses the design aspects of wind turbines. Due to randomness in wind turbines, there exist two options of lower generator rating with higher capacity ratio or higher generator rating with lower capacity ratio. Generally the last option is preferred because of higher electricity produced per rupee invested.

CHAPTER-2

Wind Turbine

<u>Wind Turbines</u>

A **wind turbine** is a rotating machine which converts the wind kinetic energy into mechanical energy. If the mechanical energy is then converted to electricity, the machine is called a **wind generator**, **wind turbine**.

Wind turbines can be separated into two types based by the axis in which the turbine rotates as Horizontal Axis Wind Turbines and Vertical Axis Wind Turbines. The former are more commonly used due to several inherent advantages, the latter being used in small scale.

Figure 2: Horizontal Axis Wind Turbine

Wind Turbine Generator units

Turbine subsystems include:

- Rotors which convert wind energy into mechanical energy of the shaft ;
- Nacelle (enclosure) which contains all the conversion equipment, generator ,gear shaft etc.
- Tower, to increase the height of the turbine systems so that higher wind speeds are captured.
- Control equipment, Cables and other Civil works.

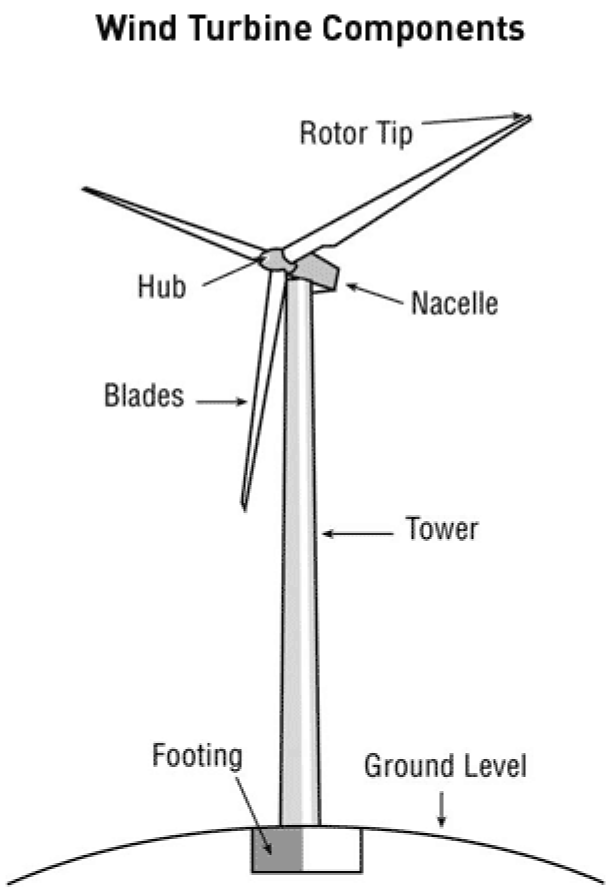


Figure 3: HAWT components

Horizontal Axis Wind Turbines (HAWTs)

Horizontal-axis wind turbines (HAWT) get their name from the fact that their axis of rotation is horizontal. They have the main rotor shaft and electrical generator at the top of a tower, and are pointed into the wind. The variability of wind distribution and speed brings up the requirement of a gear system connected to the rotor and the generator. The gear system enables a constant speed of rotation to the generator thus enabling constant frequency generation. Turbine blades are made stiff in order to prevent the blades from being pushed into the tower by high winds. Downwind machines have also been built, as they no longer require a yaw mechanism to keep them facing the wind, and also because in high winds the blades can turn out of the wind thereby increasing drag and coming to a stop. Most of the HAWTs' are upwind as downwind systems cause regular turbulence which may lead to fatigue.

HAWT advantages

• Variable blade pitch, which gives the turbine blades the optimum angle of attack.
Changing the angle of attack provides greater control over power generated and enables maximum efficiency.

• As wind energy increases with height, the tall tower in the HAWT gives access to higher wind speed. In some cases increase of even 10m height leads to increase in wind speed by 20 %

•In HAWTs' the blades move horizontally that is perpendicular to the wind and hence have minimum drag and they receive power throughout the rotation.

HAWT disadvantages

•Due to inherent large structures, construction costs are very high and so are transportation costs.

•Civil construction is costly due to erection of large towers.

•Wind turbine operation often leads to production of electronic noise which affects radar sites.

• In case of downwind HAWTs' the regular turbulence produced leads to structural failure.

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

Types of HAWTs:

➢ Mono-Blade Horizontal Axis Wind Turbine (HAWT)

Features:

1. They have lighter rotor and are cheaper.
2. Blade are 15-25 m long and are made up of metal, glass reinforced plastics, laminated wood, composite carbon fiber/ fiberglass etc.
3. Power generation is within the range 15 kW to 50 kW and service life of plant is 30 years.

Advantages:

1. Simple and lighter construction.
2. Favorable price
3. Easy to install and maintain.

Disadvantages:

1. Tethering control necessary for higher loads.
2. Not suitable for higher power ratings.

Applications:

1. Field irrigation
2. Sea-Water desalination Plants
3. Electric power supply for farms and remote loads.

➢ Twin-Blade HAWT

1. They have large sizes and power output in range of 1 MW, 2 MW and 3MW.
2. These high power units feed directly to the distribution network.

➢ 3-Blade HAWT

1. 3 blade propeller type wind turbines have been installed in India as well as abroad.
2. The rotor has three blades assembled on a hub. The blade tips have a pitch control of 0 – 30 for controlling shaft speed.
3. The shaft is mounted on bearings.
4. The gear chain changes the speed from turbine shaft to generator shaft.

Vertical axis Wind Turbines

Vertical-axis wind turbines (or VAWTs) have the main rotor shaft arranged vertically as the plane of rotation is vertical. Blades are also vertical in this arrangement. The biggest advantage of VAWTs is they don't require a yaw control mechanism to be pointed into the wind. Thus these are useful in sites where wind direction is random or there is presence of large obstacles like trees, houses etc. Also VAWTs' don't require a tower structure and can be placed nearby a ground enabling access to electrical components. Some drawbacks are the low efficiency of wind production and the fact that large drag is created for rotating the blades in a vertical axis.

VAWT advantages

• A massive tower structure is not required, as VAWTs' are mounted closer to the ground

• They don't require yaw mechanisms.

• These are located closer to the ground and hence easier to maintain.

• These have lower startup speeds than their horizontal counterparts. These can start at speeds as low as 10Kmph.

• These have a lower noise signature.

VAWT disadvantages

•VAWTs' have lower efficiency as compared to HAWTs' because of the additional drag produced due to rotation of blades.

• Even though VAWTs' are located closer to the ground, the equipment now resides at the bottom of the turbines structure thus making it inaccessible.

•Because of their low height they cannot capture the wind energy stored in higher altitudes.

Types of VAWTs

- **Persian Windmill:**

1. The Persian windmill was the earliest windmill installed. (7th Century A.D. – 13th Century A.D. in Persia, Afghanistan, and China)
2. It is a vertical axis windmill.

3. This windmill was used to grind grains and make flour.

- **Savonius Rotor VAWT:**

1. Patented by S.J. Savonius in 1929.
2. It is used to measure wind current.
3. Efficiency is 31%.
4. It is Omni-directional and is therefore useful for places where wind changes direction frequently.

- **Darrieus Rotor VAWT:**

1. It consists of 2 or 3 convex blades with airfoil cross-section.
2. The blades are mounted symmetrically on a vertical shaft.
3. To control speed of rotation mechanical brakes are incorporated. Those brakes consist of steel discs and spring applied air released calipers for each disc.

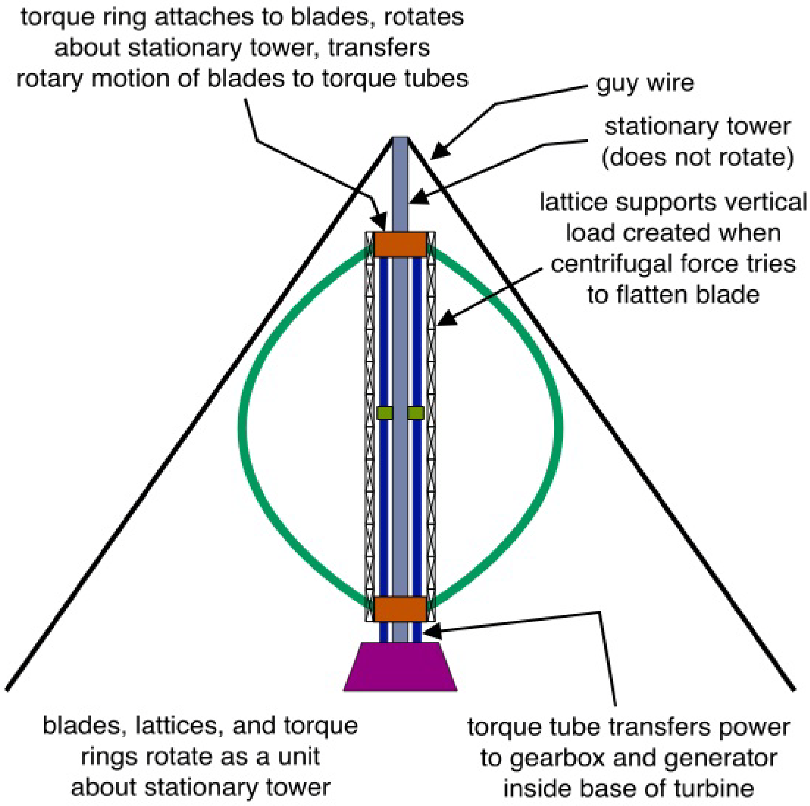


Figure 4: High Mechanical Efficiency Centrifugally Stable Darrieus Turbine

VAWT's Used in Practice:

Windterra Eco 1200 1Kw VAWT:

The aforesaid VAWT is developed by Windterra corporation. It is a technically superior product that can be used in both urban and rural areas.

Figure 5: Windterra ECO1200 VAWT

The following are the advantages of the Windterra VAWTs':

- **Omni-directional**: As in case of all VAWTs' this turbine is also omni-directional and can take in wind from any direction.
- **Turbulent-wind friendly**: Due to its omni-directional nature it a feasible product for urban areas where large obstacles such as trees and houses are there.
- **Low rotation speed**: Like all VAWTs' this rotates at lower speeds around 200rpm to 270rpm and thus produces lower noise signature.
- **Industry-leading annual output**: Due to aforesaid advantages. And the fact that this is specifically designed to operate at lower wind speed the output of the turbine is industry leading.

- **Roof-top mounting**: The VAWTs' is manufactured so as to be roof mountable without any fuss and also includes the generator etc in a complete package.

Internal Components of a Wind Turbine

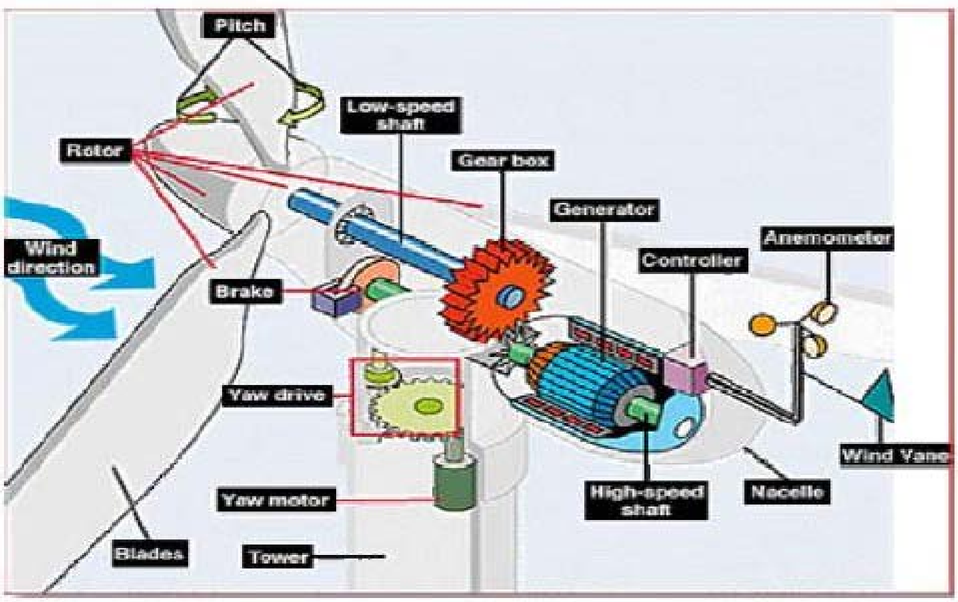


Figure 7: Internal Components of a Wind Turbine

- **Anemometer:** This device is used for measurement of speed. The wind speed is also fed to the controller as it is one of the variables for controlling pitch angle and yaw
- **Blades:** These are aerodynamically designed structures such that when wind flows over them they are lifted as in airplane wings. The blades are also slightly turned for greater aerodynamic efficiency.
- **Brake:** This is either a mechanical, electrical or hydraulic brake used for stopping the turbine in high wind conditions.
- **Controller:** This is the most important part of the turbine as it controls everything from power output to pitch angle. The controller senses wind speed, wind direction, shaft speed and torque at one or more points. Also the temp of generator and power output produced is sensed

- **Gear box:** This steps-up or steps down the speed of turbine and with suitable coupling transmits rotating mechanical energy at a suitable speed to the generator. Typically a gear box system steps up rotation speed from 50 to 60 rpm to 1200 to 1500 rpm
- **Generator:** This can be a synchronous or asynchronous Ac machine producing power at 50Hz
- **High-speed shaft:** Its function is to drive the generator.
- **Low-speed shaft**: The rotor turns the low-speed shaft at about 30 to 60 rotations per minute.
- **Nacelle:** The nacelle is the housing structure for high speed shaft, low speed shaft, gear box, generator, converter equipment etc. It is located atop the tower structure mostly in the shadow of the blades.
- **Pitch:** This is basically the angle the blades make with the wind. Changing the pitch angle changes weather the blades turn in or turn out of the wind stream.
- **Rotor:** The hub and the blades together compose the rotor.
- **Tower:** Towers are basically made up of tubular steel or steel lattice. Taller the towers greater is the amount of power generated as the wind speed generally goes on increasing with height.
- **Wind direction:** Generally erratic in nature, hence the rotor is made to face into the wind by means of control systems.
- **Wind vane:** Basically the job of a wind sensor, measuring the wind speed and communicating the same to the yaw drive, so as to turn the turbine into the wind flow direction.
- **Yaw drive:** This drive controls the orientation of the blades towards the wind. In case the turbine is out of the wind, then the yaw drive rotates the turbine in the wind direction
- **Yaw motor:** Powers the yaw drive.

CHAPTER-3

Wind Turbine Design & Characteristics

DESIGN OF THE WIND TURBINE ROTOR

There are several parameters involved in the design of an efficient yet economical wind turbine. Generally and efficient design of the blade is known to maximize the lift and minimize the drag on the blade. Now, minimization of the drag means that the aerofoil should face the relative wind in such a way that minimum possible area is exposed to the drag force of the wind. Furthermore the angle of this relative wind to the blades is determined by the relative magnitudes of the wind speed and the blade velocity. The thing to note here is that the wind velocity basically stays constant throughout the swept area but the blade velocity increases from the inner edge to the tip. Which means the relative angle of the wind with respect to the blade is ever-changing.

Now the various parameters which determine the design of the wind turbine are noted below:

Diameter of the Rotor:

Since the power generated is directly proportional to the square of the diameter of the rotor, it becomes a valuable parameter. It's basically determined by the relation between the optimum power required to be generated and the mean wind speed of the area.

Power generated,

$$P= \eta_e\eta_m C_p P_0$$

$$=1/2\eta_e\eta_m C_p A\rho V_\infty^3$$

here, $\eta_e =$ efficiency of electrical generation

$$=1/8\eta_e\eta_m C_p\pi \rho V_\infty^3 D^2$$

$\eta_m =$ efficiency of mechanical transmission

In the absence of concrete data, the following empirical formulae can be used:

$P=0.15 V_\infty^3 D^2$, for slow rotors

$=0.20 V_\infty^3 D^2$, for faster rotors

Choice of the number of blades:

The choice of the number of blades of a wind rotor is critical to its construction as well as operation. Greater number of blades is known to create turbulence in the system, and a lesser number wouldn't be capable enough to capture the optimum amount of wind energy. Hence the number of blades should be determined by both these constraints and after proper study of its dependence on the TSR. Now, let $\mathbf{t_a}$ be the time taken by one blade to move into the position previously occupied by the previous blade, so for an n-bladed rotor rotating at an angular velocity, $\boldsymbol{\omega}$ we have the following relation:

$$t_a = 2\pi/n\omega$$

Again let $\mathbf{t_b}$ be the time taken by the disturbed wind, generated by the interference of the blades to move away and normal air to be reestablished. Now this will basically depend on the wind speed, on how fast or how slow the wind flow is. Hence it depends on the wind speed **V** & the length of the strongly perturbed wind stream, say **d** Here we have:

$$t_b = d/V$$

For maximum power extraction, t_a & t_b should be equal, hence

$$t_a = t_b$$

$$\Rightarrow 2\pi/n\omega = d/V$$

$$\Rightarrow d = 2\pi V/n\omega$$

d has to be determined empirically.

Choice of the pitch angle:

The pitch angle is given by

α=I-i ,where I is the angle between the speed of the wind stream and the speed of the blades

Now as I varies along the length of the blade, α, should also vary to ensure an optimal angle of incidence at all points of the blade. Thus the desirable twist along the blade can be calculated easily. The pitch angle should be such that tan E or C_d/C_l should be minimum at all points of the rotor. Some researchers suggest the use of Eiffel polar plots, where the tangent to the Eiffel plot gives the minimum C_d/C_l ,for this situation. However for the same scale this becomes inconvenient & as C_l is generally two orders of magnitude higher than C_d it's better to plot a graph of C_d/C_l versus i. Its minimum point will represent the optimal pitch angle.

This method yields a twisted blade which basically has different pitch angles at different distances from the axis.

Power Speed Characteristics

The mechanical power that can be extracted from the wind depends heavily on the wind speed, and for each wind speed there is always an optimum turbine speed at which the wind power extracted at the shaft of the turbine is maximum, at any other speed apart from this optimum speed we get sub-standard operation of the system. So our chief goal would be to find out the optimum turbine speed over the operational range of the wind stream speeds. This thing is basically area specific, because the wind speeds would vary from place to place. Now the mechanical power transmitted at the shaft is:

$$P=0.5C_p A\rho V_\infty^3$$

As we know C_p is a function of the TSR & the pitch angle. For a wind turbine with radius R, the above formula can be written as,

$P = 0.5 C_p \pi R^2 \rho V_\infty^3$

Now as the TSR, $\lambda = \omega R / V_\infty$

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

$P_m = 0.5 C_p \pi (R^5 / \lambda^3) \omega^3 \rho$

⇨ $P_m \alpha \omega^3$

Torque Speed Characteristics

Now we know that the Torque and power curves are related as follows:

$T_m = P_m / \omega$

Using the above value for $P_m = 0.5 C_p \pi (R^5 / \lambda^3) \omega^3 \rho$

We have, $T_m = P_m / \omega$

⇨ $T_m = 0.5 C_p \pi (R^5 / \lambda^3) \omega^2 \rho$

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

Solidity

The solidity of a wind rotor is defined as the ratio of the projected blade area to the area of wind intercepted. Generally the projected blade area doesn't mean the actual blade area, it's the blade area met by the wind or projected into the wind flow.

Table 2: Solidity ratio's of various rotors

Type Of Rotor	Solidity
Savonius Rotor	1
Multi-blade water pumping wind rotor	0.7
High Speed Horizontal axis Rotor	0.01 to 0.1
Darrieus Rotor	0.01 to 0.3

Tip speed Ratio

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

$$\lambda = 2\pi RN/V_{\infty}$$

V_{∞} = Speed of Wind without any rotor intervention

R=Radius of the Rotor, which signifies the swept area

N=Rotational speed of the rotor in rps

λ= Tip Speed Ratio

The **tip speed ratio** (λ) for wind turbines is the ratio between the rotational speed of the tip of a blade and the actual velocity of the wind .It's basically non dimensional in nature and high efficiency 3-blade-turbines have tip speed ratios of 6–7.

Coefficient of Power

The coefficient of power of a wind turbine basically signifies the conversion efficiency of the wind energy of the wind into mechanical energy, which in turn is used to drive the generators. It differs from the overall system efficiency as it doesn't include the losses in transmission (mechanical) and in electrical power generation. In horizontal axis machines the theoretical limit is known as Betz limit, which is around .593(16/27 or 59.3%). For good turbines it is in the range of 35-45%.

C_p= (Ouput Power of a Wind Machine)/(Power Content of the wind stream)

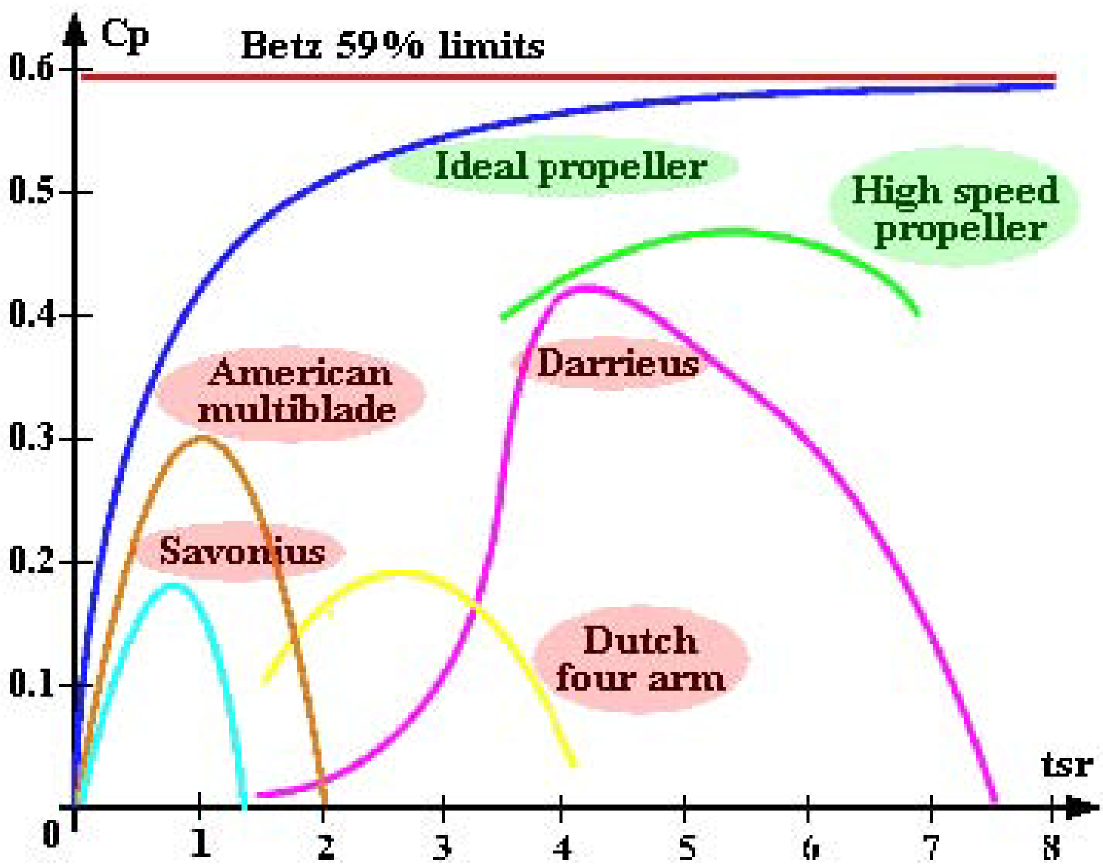


Figure 7: C_p Vs TSR curve for various types of rotors

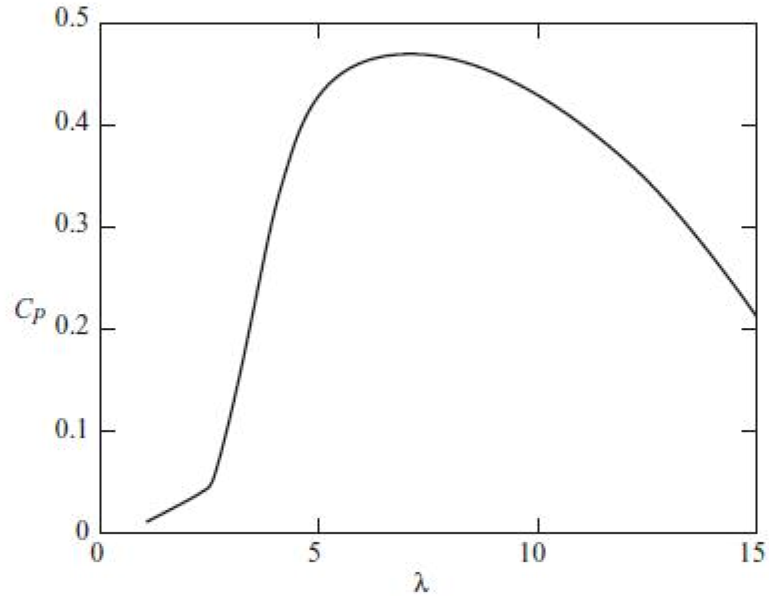


Figure 8: Power Coefficient (CP) vs. Tip Speed Ratio (λ)

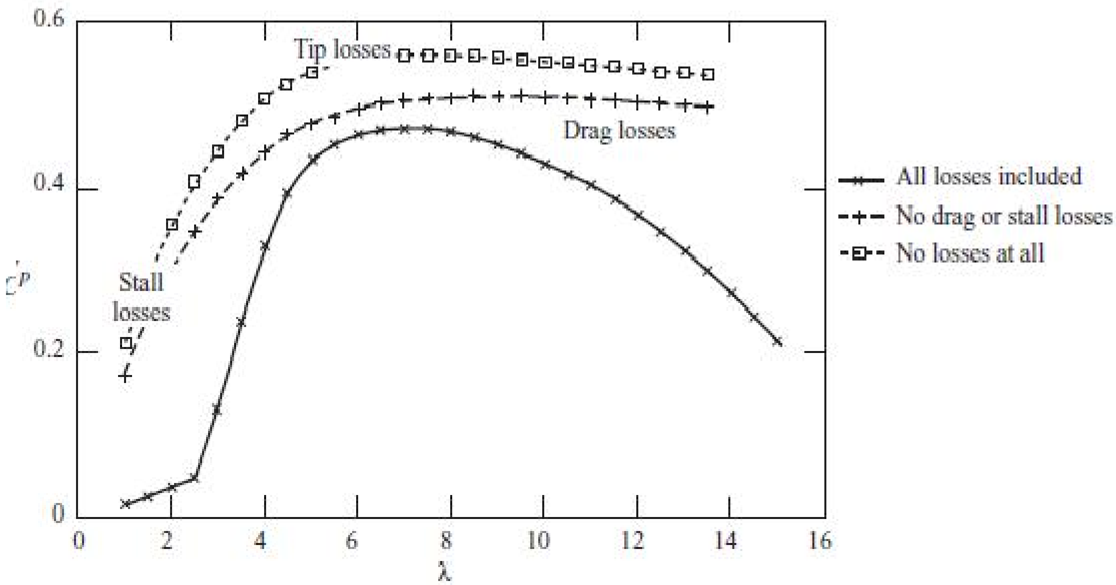


Figure 9: C_p-λ Performance Curve for a Modern Three-blade Turbine Showing Losses

Wind Turbine Ratings & Specifications

Comparison of Wind turbines is necessary from both a assessment and market competency point of view, there have been countless parameters devised to study the turbine ratings and in turn serve as a medium for comparison. One of the oft used index is the Specific Rated Capacity(SRC)**.** Which is basically the ratio between the power rating of the generator used in the system to the rotor swept area.

SRC= (Power rating of the generator)/(Rotor swept area)

The ratio generally varies between the ranges:

0.2 = >SRC= >0.6

The lower limit is for smaller rotors, and the upper for larger rotors.

Degree of freedom

Optimization of the power generated in a wind generator is done my means of two basic degrees of freedom:

1. ***Yaw orientation:*** It basically refers to the freedom that we have to change the orientation of the entire nacelle unit so that the rotor is pointed directly into the ever-changing direction of wind flow. This is explained in detail under yaw control, and is done basically by help of motors. The motors are run on the information generated from the wind vanes, which act as the sensors for this system.

2. ***Pitch of blades:*** By changing the pitch of the blades we can keep a near-constant rotation rate under the ever varying wind speeds. Generally the control is done in a manner, such that the power-generation efficiency of the turbine is optimized.
Both the pitch of the blades and the Yaw control mechanism can act as brakes for the system in case it's hit by strong gusts of wind.

CHAPTER-4

Controllers & Generators

Controllers

The wind turbine control system consists of a of sensors, actuators, and a system consisting of hardware and software which processes the input signals from the sensors and generates output signals for the actuators.

The sensors might include, for example:
• An anemometer,
• A wind vane,
• At least one rotor speed sensor,
• An electrical power sensor,
• A pitch position sensor,
• Various limit switches,
• Vibration sensors,
• Temperature and oil level indicators,
• Hydraulic pressure sensors,
• Operator switches & push buttons, etc.

The actuators might include a hydraulic or electric pitch actuator, sometimes a generator torque controller, generator contactors, switches for activating shaft brakes, yaw motors, etc.
The system that processes the inputs to generate outputs usually consists of a computer or microprocessor-based controller which carries out the normal control functions needed to operate the turbine, supplemented by a highly reliable hardwired safety system. The safety system must be capable of overriding the normal controller in order to bring the turbine to a safe state if a serious problem occurs.

Functions of a Controller in the Wind Turbine Construct

❖ Supervisory control

Supervisory control can be considered as the means whereby the turbine is brought from one operational state to another. The operational states might, for example, include:

- Stand-by, when the turbine is available to run if external conditions permit,
- Start-up,
- Power production,
- Shutdown, and
- stopped with fault.

❖ Closed-loop control

The closed-loop controller is usually a software-based system, which obviates the need for manual control. This is a form of automation in general; it adjusts the operational state of the turbine in such a manner so as to keep it operational in the required range. Basically the operating range is found out on the basis of a operating curve or characteristic. Some examples of such control loops are:

- Control of blade pitch in order to regulate the power output of the turbine to the rated level in above-rated wind speeds;
- Control of blade pitch in order to follow a predetermined speed ramp during start-up or shut-down of the turbine;
- Control of generator torque in order to regulate the rotational speed of a variable speed turbine;
- Control of yaw motors in order to minimize the yaw tracking error.

Figure 10: Low-speed Shaft speed Sensing System

❖ The safety system:

The safety system is quite distinct from the main control system of the turbine. Its eponymous function is to protect the turbine and bring it to a safe condition in case of potentially hazardous situation. This usually means bringing the turbine to rest with the brakes applied.

The safety system might, for example, be tripped by any one of the following:

• Rotor overspeed, i.e., reaching the hardware overspeed limit – this is set higher than the software overspeed limit which would cause the normal supervisory controller to initiate a shut-down (see Figure for typical arrangement of rotor speed sensing equipment on low-speed shaft);

• Vibration sensor trip, which might indicate that a major structural failure has occurred;

• Controller watchdog timer expired: the controller should have a watchdog timer which it resets every controller time step – if it is not reset within this time; this indicates that the controller is faulty and the safety system should shut down the turbine;

• Emergency stop button pressed by an operator;

• Other faults indicating that the main controller might not be able to control the Turbine

Types of Control Systems

✓ Pitch control

Pitch control is the most common means of controlling the aerodynamic power generated by the turbine rotor. It also has a major effect on all the aerodynamic loads generated by the rotor. In this control the system changes the pitch angle of the plates according to the speed of the wind. below rated wind speed, the turbine should simply be trying to produce as much power as possible, so there is no need to vary the pitch angle. Here, the pitch setting should be at its optimum value to give maximum power. Above rated wind speed, pitch control provides a very effective means of regulating the aerodynamic power and loads produced by the rotor so that design limits are not exceeded. A decrease in pitch, i.e., turning the leading edge downwind, reduces the torque by increasing the angle of attack towards stall, where the lift starts to decrease and the drag increases. This is known as pitching towards stall. Most pitch controlled turbines use full-span pitch control, in which the pitch bearing is close to the hub. It is also possible, though not common, to achieve aerodynamic control by pitching only the blade tips, or by using ailerons, flaps, airjets or other devices to modify the aerodynamic properties.
These strategies will result in most of the blade being stalled in high winds. If only the blade tips are pitched, it may be difficult to fit a suitable actuator into the outboard portion of the blade; accessibility for maintenance is also difficult.

In the process of controlling the pitch in cases of speeds above the wind speed, the rotor output power decreases, generally the input variable to the pitch controller is the error signal arising from the difference between the output electrical power and the reference power. Generally the operation below the rated speed has the controller changing the pitch in a manner so as to use the available wind stream most efficiently. The generator output hence has to be properly monitored, this would necessitate incorporation of better sensors, hence complete pitch control is generally not considered for smaller machines.

✓ Stall control

Many turbines are stall-regulated, which means that the blades are designed to stall in high winds without any pitch action being required. This means that pitch actuators are not required. Some means of aerodynamic braking is likely to be required, if only for emergencies. In order to achieve stall-regulation at reasonable wind speeds, the turbine must operate closer to stall than its pitch-regulated counterpart, resulting in lower aerodynamic efficiency below rated. This disadvantage may be mitigated in a variable-speed turbine, when the rotor speed can be varied below rated in order to maintain peak power coefficient. In order for the turbine to stall rather than accelerate in high winds, the rotor speed must be restrained. In a fixed speed turbine the rotor speed is restrained by the generator, which is governed by the network frequency, as long as the torque remains below the pull-out torque. In a variable speed turbine, the speed is maintained by ensuring that the generator torque is varied to match the aerodynamic torque. A variable-speed turbine offers the possibility to slow the rotor down in high winds in order to bring it into stall. This means that the turbine can operate further from the stall point in low winds, resulting in higher aerodynamic efficiency. However, this strategy means that when a gust hits the turbine, the load torque not only has to rise to match the wind torque but also has to increase further in order to slow the rotor down into stall. This removes one of the main advantages of variable-speed operation, namely that it allows very smooth control of torque and power above rated.

✓ Generator torque control

The torque developed by a fixed-speed (i.e., directly-connected) induction generator is determined purely by the slip speed. As the aerodynamic torque varies, the rotor speed varies by a very small amount such that the generator torque changes to match the aerodynamic torque. The generator torque cannot therefore be actively controlled. If a frequency converter is interposed between the generator and the network, the generator speed will be able to vary. The frequency converter can be actively controlled to maintain constant generator torque or power output above rated wind speed. Below rated, the torque can be controlled to any desired value, for example with the aim of varying the rotor speed to maintain maximum aerodynamic efficiency. There are several means of achieving variable-speed operation. One is to connect the generator stator to the network through a frequency converter, which must then be rated for the full power output of the turbine. Alternative arrangements include a wound rotor induction generator with its stator connected directly to the network, and with its rotor connected to the network through slip rings and a frequency converter. This means that the frequency converter need only be rated to handle a fraction of the total power, although the larger this fraction, the larger the achievable speed range will be. A special case is the variable slip induction generator, where active control of the resistance in series with the rotor windings allows the torque/speed relationship to be modified. By means of closed-loop control based on measured currents, it is possible to maintain constant torque above rated, effectively allowing variable speed operation in this region. Below rated it behaves just like a normal induction generator

✓ Yaw control

Turbines whether upwind or downwind, are generally stable in yaw in the sense that if the nacelle is free to yaw, the turbine will naturally remain pointing into the wind. However, it may not point exactly into wind, in which case some active control of the nacelle angle may be needed to maximize the energy capture. Since a yaw drive is usually required anyway, e.g. for start-up and for unwinding the pendant cable, it may as well be used for active yaw tracking. Free yaw has the advantage that it does not generate any yaw moments at the yaw bearing. However, it is usually necessary to have at least some yaw damping, in which case there will be a yaw moment at the bearing. In practice, most turbines do use active yaw control. A yaw error signal from the nacelle-mounted wind vane is then used to calculate a demand signal for the yaw actuator. Frequently the demand signal will simply be a command to yaw at a slow fixed rate in one or the other direction. The yaw vane signal must be heavily averaged, especially for upwind turbines where the vane is behind the rotor. Because of the slow response of the yaw control system, a simple dead-band controller is often sufficient. The yaw motor is switched on when the averaged yaw error exceeds a certain value, and switched off again after a certain time or when the nacelle has moved through a certain angle. More complex control algorithms are sometimes used, but the control is always slow-acting, and does not demand any special design considerations. One exception is the case of active yaw control to regulate aerodynamic power in high winds, as used on the variable speed Gamma 60 turbine. This clearly requires very rapid yaw rates, and results in large yaw loads and gyroscopic and asymmetric aerodynamic loads on the rotor. This method of power regulation would be too slow for a fixed-speed turbine, and even on the Gamma 60 the speed excursions during above-rated operation were quite large.

Generators

A generator is an electrical machine which helps in generating electricity by using the mechanical energy of a prime mover. Wind or Aero-generators are basically wind turbine-generator sets, i.e. a propeller or rotor attached to a turbine which in turn is coupled with an electric generator. The generator is further connected to appropriate electronic devices that help in its connection and synchronization to the electrical grid.

Generators are basically of two different types:

a) Synchronous Generators

b) Asynchronous Generators

The basis of this categorization is the speed of operation of generators. Synchronous generators are run at synchronous speed (1500 rpm for a 4 pole machine at 50Hz frequency) while asynchronous generators run at a speed more than the synchronous speed.

SYNCHRONOUS GENERATOR

Synchronous generators are doubly fed machines which generate electricity by the principle of electromagnetic induction. The rotor is rotated by a prime mover. The result is a current, which flows in the stationary set of rotor conductors. Now this produces a magnetic field which in turn induces a current in the stator conductors. This is the current which we use finally as the output.

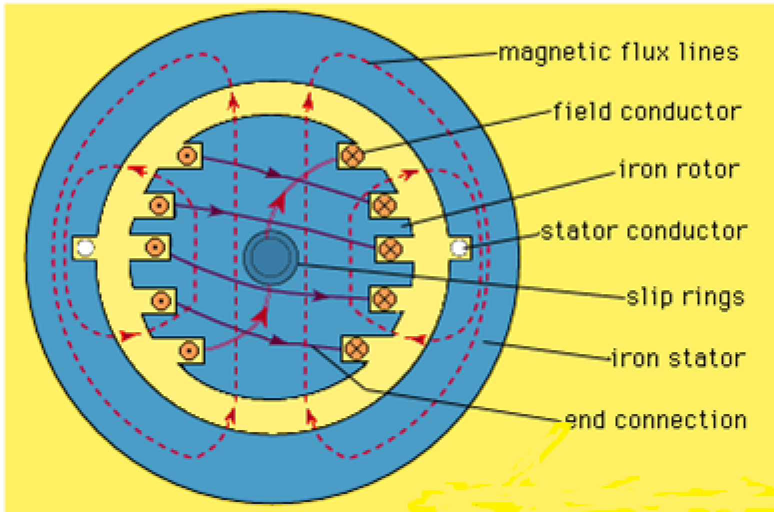


Figure 11: Synchronous Generator

This rotating magnetic field induces an Alternating voltage, by the principle of electromagnetic induction, in the stator windings. Generally there are three sets of conductors distributed in phase sequence, so that the current produced is a three phase current. The rotor magnetic field is generally produced by means of induction, where we use either permanent magnets (in very small machines) or electromagnets in larger machines. Also the rotor winding is sometimes energized with direct current through slip rings and brushes. Sometimes even a stationary field winding, with moving poles in the rotor may be the source of the rotor magnetic field. Now this very setup is been used in automotive alternators, where by varying the current in the field winding we can change and control the alternator voltage generated. This process is known as excitation control. Basically the problem which plagues the electromagnets is the magnetization losses in the core, this is absent in the permanent magnet machines. This acts as an added advantage, but there is a size restriction owing to the cost of the material of the core.

ASYNCHRONOUS GENERATOR

Asynchronous generators or Induction generators are singly excited a.c. machine. Its stator winding is directly connected to the ac source whereas its rotor winding receives its energy from stator by means of induction. Balanced currents produce constant amplitude rotating mmf wave.

The stator produced mmf and rotor produced mmf wave, both rotate in the air gap in the same direction at synchronous speed. These two mmf s combine to give the resultant air-gap flux density wave of constant amplitude and rotating at synchronous speed. This flux induces currents in the rotor and an electromagnetic torque is produced which rotates the rotor. Asynchronous generators are mostly used as wind turbines as they can be operated at variable speed unlike synchronous generator. Two kinds of asynchronous generators are used namely

a) Squirrel cage induction generator (SCIG)

b) Doubly fed induction generator (DFIG)

➢ SQUIRREL CAGE INDUCTION GENERATOR

A squirrel cage rotor is so named due to the shape which represents a cage like structure; it basically is the rotating part of the generator. Being cylindrical in nature, it's mounted on the shaft. The internal construction relates to the cage structure and contains longitudinal conductive bars (made of aluminum or copper) set into channel like constructs and connected together at both ends by shorting rings forming a proper cage-like shape. The core of the rotor is built of a stack of iron laminations, so as to decrease the eddy current losses.

Figure 12: Squirrel Cage rotor

The current flowing in the field windings in the stator results in the setting up of a rotating magnetic field around the rotor. This magnetic field cuts across the shorted rotor conductors resulting in electromagnetic induction which induces a voltage and in turn a current in the rotor windings. The magnitude of both the induced entities depends directly on the relative speed of the rotor with respect to the stator; this quality is basically called the slip of the motor. Slip basically signifies the difference between the speeds of the rotor and synchronous stator field speed. The rotor is carried around with the magnetic field but at a slightly slower rate of rotation.

➢ DOUBLY FED INDUCTION GENERATOR

DFIG is Double Fed Induction Generator, a generating principle widely used in wind turbines. It is based on an induction generator with a multiphase wound rotor and a multiphase slip ring assembly with different brushes for access to the varied rotor windings.

For wind power applications, this type of machine has distinct advantage over the conventional type of machines.

- The rotor circuit is basically controlled by a power electronics converter. Now this makes it possible for the induction generator to act both as a source and sink for reactive power. This allows for power system stability and allows the machine to support the grid during severe voltage disturbances (low voltage ride through, LVRT) also it allows for reactive power compensation of the system.
- The control of the rotor voltages and currents enables the induction machine to remain synchronized with the grid while the wind turbine speed varies. This allows for the proper usage of the wind stream, since a variable speed drive can derive greater power from the wind stream, as compared to a fixed sped drive
- Another factor which reduces the cost of the converter, apart from the initial investment is that only fraction of the Mechanical power, typically 25-30 %, is fed to the grid through the converter, the rest is fed to grid directly from the stator. This in turn enhances the efficiency of the DFIG.

CHAPTER-5

Grid Connection

Types of Wind Energy Systems

Wind Energy systems are classified into the following categories

- Wind Electric Systems connected to the Grid(without need for storage)
- Standalone Electric Systems(with energy storage)
- Wind Mechanical energy systems(without energy storage)
- Hybrid Energy Systems that is wind diesel, solar electric, battery hybrid etc

Wind to Electrical Energy Conversion

Some considerations while selecting the system are as underlined:

1. Types of Output
   1.1. D.C
   1.2. Variable Frequency AC
   1.3. Constant Frequency AC
2. Wind Turbine Rotor Speed
   2.1. Constant Speed with speed pitch control and gear
   2.2. Nearly Constant Speed
   2.3. Variable Speed with fixed pitch blades
3. Utilization Aspects
   3.1. Stand Alone or Grid Connected
   3.2. Energy storage requirements for hazard periods

Constant Speed Constant Frequency System

This system is obtained naturally from Synchronous Generators. As in all wind turbines the shaft of the turbine is connected to the shaft of the generator through a gear box. In order to maintain torque output constant variable pitch control is required. These systems are required because most modern wind farms are grid connected, which implies that constant frequency is a necessity.

Examples: Smith Putman, 1.25 MW Ruthland, USA (1945).

Variable Speed Constant Frequency

Thyristor convertors are used in these systems. The turbine has variable speed and so has the gear system, in fact the input to the generator system is also a variable speed. Thus the output produced by the generator is a variable frequency output. This output is then rectified by convertors to obtain a appropriate output. Thus this system doesn't require any pitch control and the efficiency of wind generation is optimal. This system however is expensive because of the additional cost of rectifier inverter.

Nearly Constant Speed and Constant Frequency of Grid

These systems use induction generators, these systems thus have +/- 10 % tolerance. The induction generator draws reactive power from the grid. To meet the reactive power requirements Static VAR systems, Synchronous Condensers etc are used.

Small and Medium units rated 100KW to 300Kw typically use this system. This is more popular in India.

Energy Storage Requirements with Wind Energy Systems

Standalone systems require energy storage. Excess electrical energy developed during high loads is utilized for storage for later purposes. In grid connected systems, in case of excess power the energy is fed to the grid, and in low load periods energy is stored in batteries.

Deficit power generation occurs when power delivered P_D is less than electrical load $P_{L.}$

$$\Delta P_D = P_L + P_D$$

During Deficit, the solutions are

- Grid Power is supplied to the load
- Stored Energy is let out
- Diesel power generator is used to feed the plant

Control and Monitoring Systems of a Wind Farm

The complete wind farm has a control system located centrally to monitor all important variables in system generation.

The variables like voltage, power, current, power factor, bearing temperature, rotor speed, wind speed, wind direction, etc are measured and equivalent digital signals are transmitted via the control cables through to the master controller.

The Control has 3 levels

- Distribution Network Control System
- Master Wind Farm Controller
- Unit WTG Controller

Signals are transmitted via radio signals. The power level is set by the station control room. The station controller monitors various units and receives signals from central controller for a specific power output.

Introduction to Grid Connection

Power and voltage quality of output from a wind turbine is not constant. Hence some form of modulation or filtering is required before connecting to Grid. This is difficult because the wind speed is random in nature and a Weibull curve is used to denote this randomness and determine the probabilistic variety of wind.

Voltage Fluctuations

The voltage Fluctuations are due to randomness of wind. Wind speed and direction direction varies also with height.

The reactive power consumed in case of a asynchronous generator depends on active power generated. It is inversely proportional to the active power generation. For this reason reactive power compensation is required, this is achieved through Static VARs, Capacitor Banks, and

Synchronous Condensers etc. Voltage fluctuations affect sensitive electronic devices and leads to their damage.

Derivation of Fluctuation in Voltage

The variation of reactive power injected into the grid is ΔP

Corresponding change in reactive power absorbed from grid is ΔQ

Then Voltage Fluctuations

$$\Delta V/V \approx \Delta P*R - \Delta Q*X$$

- $\Delta V/V \approx \Delta S*Z*Cos(a + b)$

R= Resistance of the grid impedance (p.u)

X= Reactance of the Grid impedance (p.u)

ΔS= Apparent power variation = $(\Delta P^2 + \Delta Q^2)^{1/2}$

Z= Grid impedance amplitude

A= Grid Impedance angle

B= $Tan^{-1}(\Delta Q/\Delta P)$

Electrical Dynamics of Wind Turbine Generator Model

The State Space equations are

$dV_c/dt = (-D_2/R_LC * V_C) - (D_1/C * I_L)$

$dI_L/dt = ((D_1-1)/L * V_C) - (R_G/L * I_L) + E_f/L$

The above equations descibe overall system behaviour including both steady state and dynamic operation.

Reactive Power Exchange Capability

The variable load shown represents an inverter connected to the power grid. A necessary condition for proper operation is that capacitor voltage is maintained close to a paticular value.

Inverter parameter

$M_f = (C_2^2/V_C^2 + (I_2^2 * \dot{\omega}^2 *L^2)/|V_3|^2)^{1/2}$

$Cosb= C_2*2^{1/2}/ V_C' * M_f$

C_2 is a user defiened parameter which determines the amunt of power exchange

I_2 is the output current of the boost converter

V_C' is the reference Dc voltage

L is the inductance used for grid connection

Influences of Grid Parameter on Flicker

Fault Level:

A simulation test when carried out in two cases of grid impedance shows inverse realationship between flicker level and fault level

X/R ratio of Grid Impedance

- The X/R ratio of the grid impedance is observed in terms of impedance angle
- Flicker is inversely proportional to the impedance angle till angle reaches minimum point , after which flicker begins to increase
- Minimum point of voltage fluctuation is at

$\beta+\alpha=90^o$

α is obtained from $\Delta Q/\Delta P$ of Q-P characteristic.

CHAPTER-6

Modern Trends in Wind Farms

Basic Offshore wind technology

Offshore Wind Turbines as their names suggest are Wind Turbines that are setup on the sea, generally in shallow water less than 30 meters in depth. Apart from the fact that they are setup in the sea bed, they are based on same technology as onshore wind turbines with similar components and control structure and with a expected lifespan that is on similar line to their offshore counterpart. The main difference is their size where a typical onshore turbine being installed would have a height to tip of between 100 meters and 120 meters with the tower height of about 60 to 80m, and blades between 30 and 40m long. Most offshore wind turbines would be smaller compared to their onshore counterparts.

One of the constraints facing onshore wind turbines are that the transportation as well as construction costs are very high as the equipments are large and bulky. In case of onshore turbines transportation is relatively cheaper but challenges exist in setting up a offshore wind turbine. So in both cases these two problems are comparable. It is more cost –effective to erect larger turbines that would have higher energy yields. Like onshore wind turbines offshore turbines are also designed and tested for adverse weather conditions and they also act similarly in case of high wind speeds above furling speed, they turn their blades in and stop. The offshore turbine components are designed and coated for protection against corrosion.

Historical Development

Conducting research and development of offshore wind power began in the nineteen seventies and is mainly concentrated in Europe and the United States. It can be roughly divided into 5 periods.

- **1977–1988:** National research on resources and technologies of offshore wind farms in Europe
- **1990–1998:** European offshore wind farm research, a number of experimental projects developed.
- **1991–1998:** Medium-sized offshore wind farm.

- **1999–2005:** Development of large-scale wind farm and large-scale offshore wind turbine.
- **2005–present:** Large-scale offshore wind farm.

With 30 years of research behind it, offshore wind technology has reached a mature stage and is seeing worldwide implementation.

From 1997 to 2004, the average annual growth rate of the global installed capacity of wind power was 26.1. Gradually the attention of energy production is shifting from onshore to offshore production. By August 2006, 21 offshore wind powers had been built around the entire world, which were located in Denmark, the United Kingdom, Ireland, Sweden, the Netherlands, and Germany.

European Wind Energy Association predicted that the development of offshore wind power will become an important source of energy during the next 15 years. It is expected that between 2010 and 2015 European offshore wind power capacity will reach a total of 10 GW, and will meet one-third of the electricity demand of Europe.

OFFSHOREWIND TURBINE DEVELOPMENT

A. 500kW-class Prototype:

In 1970's the first research of offshore wind turbines was started in the northern European countries of Netherlands, Germany and Denmark. The first prototypes of 500Kw power wind turbine designs were designed and tested.

B. The First Generation Megawatt-class Wind Turbine:

In early 2000's the first generation megawatt class offshore wind turbines were installed and perfected. This opened up a new chapter in offshore wind turbine development. For this purpose onshore turbines were modified with anti corrosion features and installed. Also ship maintenance equipment was developed. The first large wind farms were installed in this period.

C. The Second Generation Megawatt Wind Turbine:

The second generation wind turbine for offshore deployment consisted of turbines with ratings of 3-5 MW. The requirement of offshore wind turbine, with special requirement of anti corrosion features was perfected. Normally these turbine rotors are 90-115 m long. High dependability and higher energy efficiency is ensured due to robust design .

D. The Third Generation Megawatt Wind Turbine:

The third generation offshore wind turbine consists of turbines with ratings greater than 5 MW. As it is more cost effective to have larger turbines that have higher energy yields. The diameter of such turbines are typically in the range of 120m .

At present, the manufacturers which already have the commercial production capacity of offshore wind power generation equipment are mainly in Vestas (Denmark), Bonus (Denmark), NEG-Micon (Denmark), GE Wind Energy (United States), Nordex (Germany), Enercon (Germany), REpower(Germany.

Development of offshore wind farm-key technologies

1. Optimal configuration and evaluation of offshore wind farm:

Evaluation of wind farm takes place by several methods first of which is wind speed forecasting methods which estimate the wind speed distribution with weibull distribution curve. The wind speed is measured by anemometers and the weibull parameters are estimated which gives and accurate distribution of wind speed. Using this methodology the energy density of a place can be determined and consequently energy that can be produced in a year.

2. Electrical transmission and grid-connection:

In order to optimize the generated output from a offshore wind farm it is important to design a lossless electrical transmission and grid connection. This is done primarily by laying submarine cables from wind farms. These cables must be operated in HVDC mode of transmission as AC cable transmission is lossy because of line charging and impedance drops. To avoid damage to the cables these cables must be buried. Offshore wind farms are generally connected and operated in 30-33 kV voltage levels. This power is then transmitted through HVDC link to a 150 kV substation onshore and is subsequently connected to the grid. Voltage levels of grid connection are determined by power flow and stability analysis.

3. Access and stability operation of offshore wind farm:

Voltage stability of the operation demands that there should not be any voltage flicker or disturbance in the voltage level. Generally operation in fixed speed mode results in this problem, in case of variable speed constant speed system the voltage stability is generally higher. Voltage stability of grid-connected operation is small disturbance voltage stability.

4. Foundations of wind turbines:

There are no technical boundaries for installing offshore wind turbines, however it is cost prohibitive and requires specialist equipment to transport and install the huge towers. Also timing is crucial as good weather is a prerequisite to installing these system.

- **Traditional concrete foundation**

These utilize techniques similar to bridge construction to keep the turbines in upright position. The foundations are built in a dry dock near the sites and then transported to the sites. These foundations are then filled with concrete or gravel to increase their weight so that they can support the large structures. Vindeby offshore wind farm and Tunoe Knob wind farm are examples of this traditional foundation technique. The water depths at Vindeby and Tunoe Knob vary from 2.5 to 7.5 m. These are generally preferred for depths upto 10m as beyond this depth the gravity structures become cost prohibitive.

- **Gravity+ Steel foundation**

One of the advances in gravity foundation is that nowadays steel structures are used instead of concrete foundations. These usually consist of a cylindrical steel structure on top of a flat steel box at the seabed. The disadvantage of this system is that it requires a seabed and also its is difficult to move due to large weight.

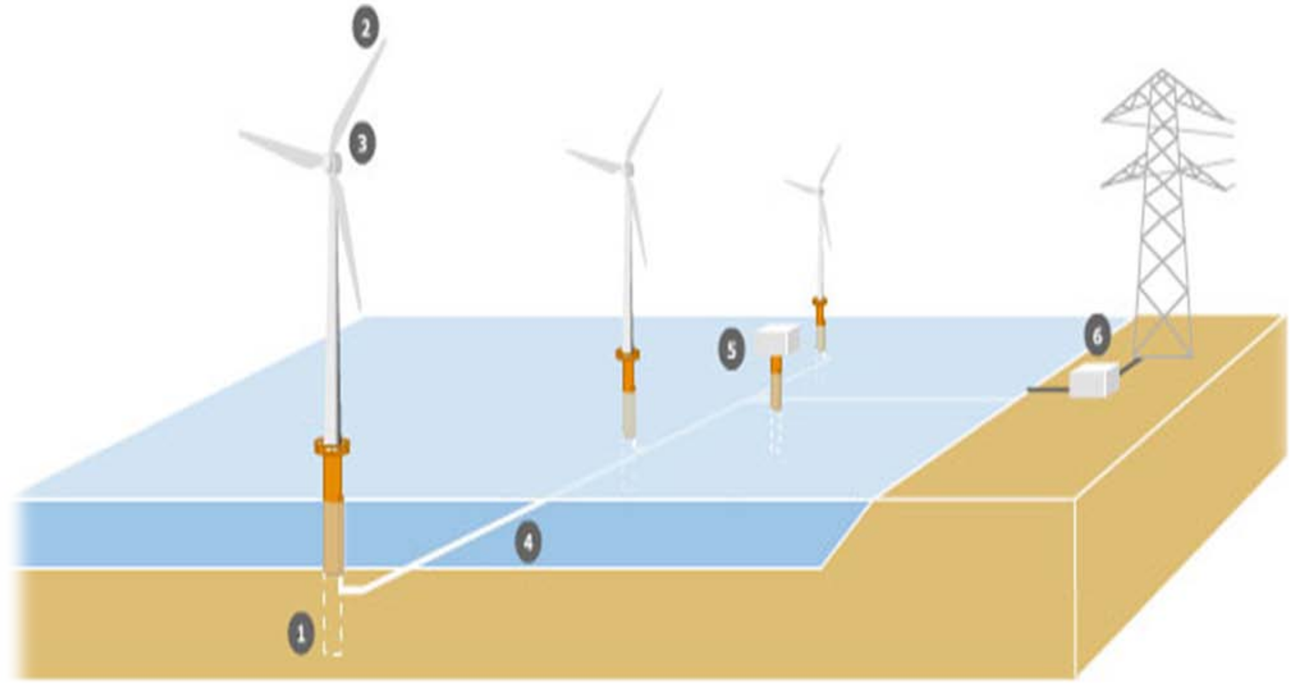
- **Monopile foundation**

The monopole foundations increase the effective height of the wind turbine into the seabed. The foundation consists of a steel pile of diameter 3.5-4.5 m driven 10-20 m into the seabed. One of the biggest advantages is that this system doesn’t require any preparation of the seabed. It is not suitable in case heavy boulders are present on the seafloor. In that case the boulders need to be blasted and the seabed drilled in order to lay a proper foundation. The foundation consists of a steel pile with a diameter between 3.5 and 4.5 m.

- **Tripod foundation**

The tripod foundation is based on the offshore industry experience, it utilizes three- legged steel jackets for proper foundation. In this case at the end if the wind turbine tower structure emanate three legs of steel piles that are driven 10-20 m into the seabed. The three legged structure gives higher stability at large depts. And also requires lesser preparation of seabed. This type of foundation is suitable at water depths higher than 20 m.

Simplified Off-shore Wind Farm



1- Undersea Piles
2- Aerodynamically shaped blades
3- Nacelle
4- Subsea cables
5- Offshore transformer
6- Substation on land

Figure 13: Simplified Off-shore Wind Farm

The following are the steps followed for the installation and operation of an offshore system:

- After initial selection of site, piles are driven into the seabed, at the selected spots. The base of the piles is protected against corrosion and erosion protection schemes are put into place.
- The top of the foundation is generally brightly painted so as to make it visible to ships; the maintenance chamber is setup at this spot, for the ease of access.

- Turbines are assembled by means of barges and powerful sea cranes, once its assembled sensors are mounted on the turbine. These sensors detect the wind direction and turn the nacelle into the direction of wind flow.
- This enables the proper functioning of the rotor, generally at its rated wind speed. The rotor is connected to a shaft inside the nacelle, this shaft is further connected to a gearbox, which steps up the speed to around 1200-1500 rpm.
- The generator coupled with the turbine system operates at this speed, and generates power.
- Subsea cables are used to transmit the power to an offshore transformer set, which then converts it to 33 kV high voltages. This is then transmitted to the grid substation on land by use of cables.

Advantages of Offshore over Onshore

Some of the advantages of offshore wind power are

- Mean wind speeds over sea are 25 % higher than that on land
- Offshore wind farms don’t have to deal with land acquisition problem
- They have higher capacity utilization than onshore counterparts.
- Comparable wind speeds can be achieved at lower heights in case of offshore wind farms than onshore wind farms.
- Fatigue loads wind turbines are smaller, increasing their lifespan.
- Wind direction is dominant and stable.

Drawbacks

Compared with land, offshore wind turbines must be fixed on the seabed, which demand a more solid supporting structure. Submarine cables are needed for transmission of electricity, and special vessels and equipments are required for building and maintenance work. These factors create high costs, with double or triple the cost in land.

OFFSHORE WIND POWER DEVELOPMENT ABROAD

A. Denmark:

As the world's wind power industry's pioneers and leaders, Demark has a global market share of more than 1/3. At the end of September 2009, 209 MW large offshore wind power was completed at Horns Rev, this being the largest such project in the world. It is estimated that wind power generation will account for 50% of all the country's total generating capacity by 2030.

B. Germany:

By 2010, installed capacity of wind energy will be increased to 3000MW. Due to the lack of suitable venues, the land-based wind power construction will be slow down in the future resulting in shift to offshore wind power construction. Examples include the Bor-kum and Butendiek wind farms.

C. United Kingdom:

In United Kingdom, two large-scale offshore wind farms at NorthHoyle and ScrobySands with total installed capacity of 60MW have been put into use. Furthermore several new projects are in the pipeline.

Aggregation

Aggregation is the phenomenon which enables large power systems to be designed independent of peak load values of individual user. According to this all electrical demand and supply are essentially random in nature and on a aggregated basis the individual power generators supply issue don't matter much. In case of a single wind farm the voltage fluctuations may be there but this doesn't demand the creation of a parallel generation system for compensating the entire fluctuation of the wind farm.

For example we can say that the minimum demand from a domestic load is onder of a few watts the average would be higher and the peak demand about 5-10 times the average demand. If the peak demand of each household were considered in designing the power system then it would be a huge demand requiring impossible levels of investment. Aggregation however smoothens the demand from all sectors- domestic, industrial, and commercial so that maximum demand would be 1.5 times the average national demand

In order to meet the random nature of demand and supply large power systems have several methods which are outlined as follows:

- Inertia of the generating plant are very important. The mechanical and thermal inertia in the boilers and turbo-alternators of coal and nuclear power stations helps keep the system stable.
- System voltage levels or frequency for that matter are rarely exact to the optimal value, there are constant fluctuations in these levels.
- In large systems there are also several plants which operate at below full potential, these can be operated in case the generation of other plants fall.
- There are also several plants which are not operational and can be called into operation within few minutes.

It's the aggregation of demand and supply, plus the effective management of the power system that guards the system against any sudden losses in capacity. Also aggregation is important in introduction of large scale wind farms. As large number of wind farms are introduced, the largely distributed wind direction distribution is compensated for and thus power produced is average.

CHAPTER-7

A study of Indian Wind Energy Potential

Indian Scenario

India’s Market Overview of Wind Energy

India has a vast supply of renewable energy resources. India has one of the world’s largest. Programs for deployment of renewable energy products and systems, with wind energy being one of the highest with 11087MW installed.

Table 3: States with strong potential: (potential MW /installed MW)

States with strong potential	Potential MW	Installed MW
Andhra Pradesh	8285	93
Gujarat	9675	173
Karnataka	6620	124
Madhya Pradesh	5500	23
Maharashtra	3650	401
Orissa	1700	1
Rajasthan	5400	61
Tamil Nadu	3050	990
West Bengal	450	1

The Indian wind energy scene is upbeat, with a large number of forays being made by multinationals like vestas, gamesa, GE power etc. and with suzlon making brisk pace in the international market, the nations wind potential is rightly being tapped. Here we analyze the wind potential of four distinct spots on the subcontinent.

Weibull Distribution

We have used the weibull distribution curve here.

The probability density function of a Weibull random variable **V** is:

$$f(V) = \left(\frac{K}{C}\right)\left(\frac{V}{C}\right)^{K-1} exp\left[-\left(\frac{V}{C}\right)^{K}\right]$$

Where, K > 0 is the *shape parameter* and C > 0 is the *scale parameter* of the distribution. V is wind speed measured at different intervals in a day.

Using the method of least square method we evaluate he values of the weibull parameters **k** & **c.**

The cumulative distribution function for the Weibull distribution is

$$F(V) = 1 - exp\left[-\left(\frac{V_i}{C}\right)^{K}\right]$$

Now representing the above function in a linear fomat, so as to facilitate the use of least square method we get,

$$Y=A_1+A_2X$$

Where $Y=\ln [\ \ln((1-F(V))^{-1})\ ]$

$X=\ln(V_i)$

$A_1=-K*\ln(C)$

$A_2=K$

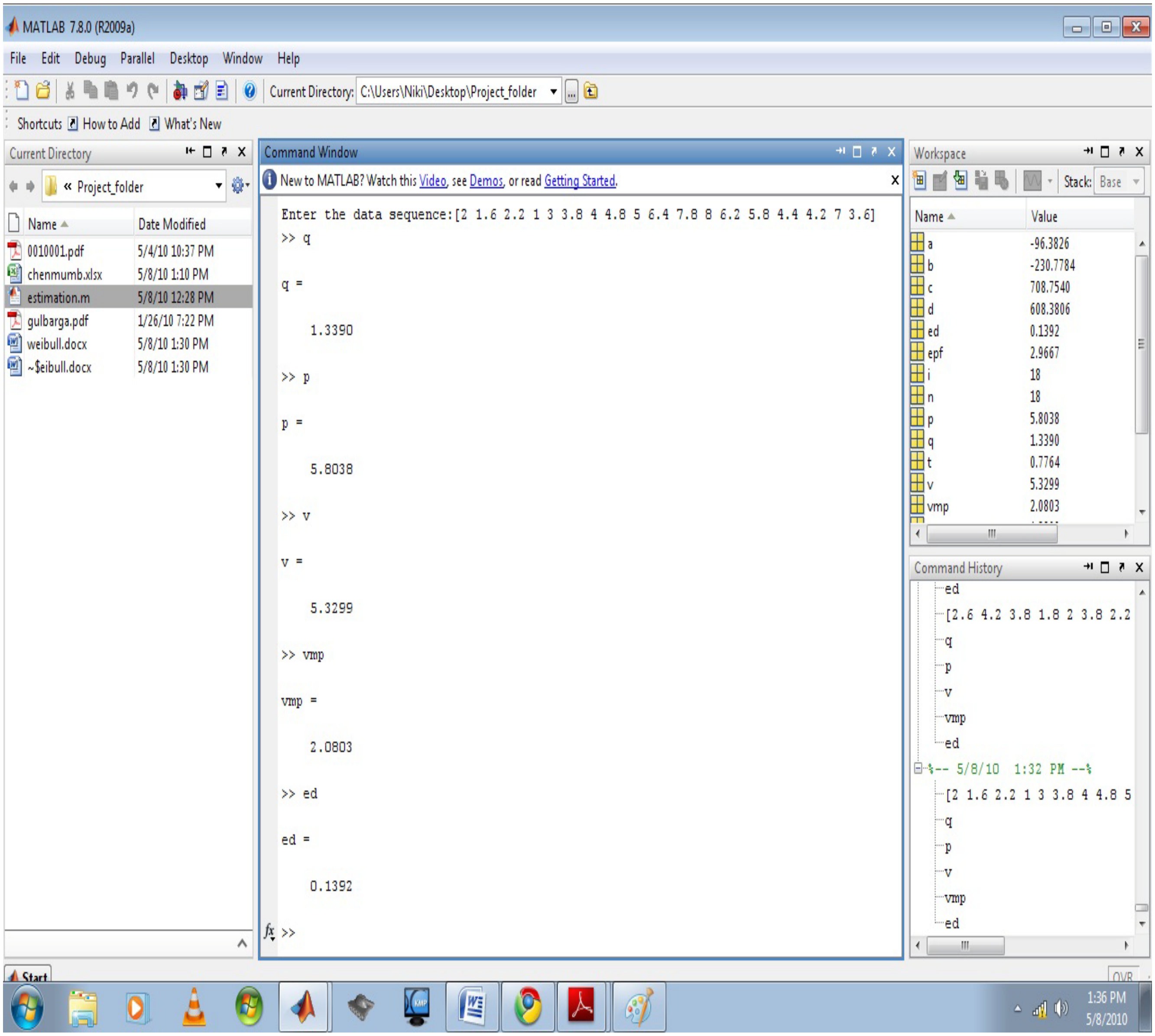
Using the above relation, we compute K & C by means of least square method, as given by the following MATLAB code.

Program code:

```
clc;
clear all;
close all;
x=input('Enter the data sequence:');
n=length(x);
x1=0;
y1=0;
w=0;
z=0;
a=0;
b=0;
c=0;
d=0;
for i=1:n
   w=log (x(i));
   z=log(-log(1-(i/(n+1))));
   x1=x1+z;
   y1=y1+w;
   a=a+z*w;
   c=c+w*w;
end;
a=n*a;
b=x1*y1;
c=n*c;
```

```
d=y1*y1;
x1=x1/n;
y1=y1/n;
q=((a-b)/(c-d));
p=exp(y1-(x1/q));
v=p*gamma(1+1/q);
vmp=p*(1-1/q)^(1/q);
t=exp(-(vmp/p)^q);
epf=gamma(1+1/q)+3*q/((gamma(1+1/q)+1/3)^3);
ed=0.00031*v^3*epf;
```

The Ouput Sequence for a particular input sequence is given as



The following table enlists the full set of data and outputs

Table 4: Estimated Energy Density Chennai

Place	**Date**	**Data Set (m/s)**	**K**	**C**	**Vavg (m/s)**	**Vmp (m/s)**	**Energy density ($Kwh/m^2/day$)**
Chennai	30th april	2 1.6 2.2 1 3 3.8 4 4.8 5 6.4 7.8 8 6.2 5.8 4.4 4.2 7 3.6	1.339	5.8038	5.3299	2.0803	0.1392
Chennai	3rd May	1 3 2.1 1.6 3.1 4 4.2 4.8 2.8 6.2 5.8 7.8 5.4 4 3.8 3.4 3.6 2	1.1006	5.4755	5.2825	0.6225	0.1131
Chennai	4th May	2 3.5 4 4.5 6 6.8 5 5.2 5.4 2.2 4.2 3.8 5.8 6.4 6.6 4.2 3 5.6	1.1115	7.0771	6.8057	0.8942	0.244
Chennai	5th May	2 3.8 2.4 4.2 2.6 1.6 4 5.2 5 3.6 6.4 6 5.8 3 4.4 4.6 2.4	1.067	5.9525	5.804	0.4449	0.1457

Table 5: Estimated Energy Density Mumbai

Place	Date	Data Set (m/s)	K	C	Vavg (m/s)	Vmp (m/s)	Energy density ($Kwh/m^2/day$)
Mumbai	30th april	2 3.4 2.8 3 2.6 3.2 4 4.5 5.2 7 5.6 7.8 4.2 6.6 1.6 4.4 3.6	1.0433	6.347	6.24	0.3007	0.1774
Mumbai	3rd May	3 2.8 1.2 2.2 2 3.2 4.4 1.8 4 4.8 5.2 4.5 6.4 6 5 4.2 3.8 5.2	1.5156	5.0034	4.5113	2.4563	0.0944
Mumbai	4th May	2.8 1.4 2.6 4.2 3 2 2.5 5 4.8 6.6 7.2 6.4 5.2 4 3.4 3.8	1.3509	5.42	4.9746	2.0001	0.1141
Mumbai	5th May	3.2 2.8 2.6 1.6 2.2 3.8 4.4 5.2 4.6 4 5.8 7 6.2 4.8 3.6 5	1.7032	5.2768	4.7076	3.139	0.1186

Table 6: Estimated Energy Density Delhi

Place	**Date**	**Data Set (m/s)**	**K**	**C**	**Vavg (m/s)**	**Vmp (m/s)**	**Energy density ($Kwh/m^2/day$)**
Delhi	30th april	2.4 2 2.8 1.6 3 3.8 4.2 4.8 5.2 3.6 4 5 6.8 7.2 7.8 4.6 5.4 4.8	1.9835	5.2576	4.6602	3.6914	0.1307
Delhi	3rd May	3.2 2 2.8 3.4 4 6 4.4 5.6 5.9 2.6 6.2 4.2 3.8 6.2 4.8 4.6 3.8 4.2 2.6	1.0569	6.5956	6.4533	0.4155	0.1985
Delhi	4th May	2 2.6 2.8 3 3.2 4.2 3.8 4 3.6 2.4 1.2 4.2 4.4 4.6 4.8 4.2 3.8 4	1.4396	4.7647	4.3246	2.0902	0.0794
Delhi	5th May	4.8 4 2.2 1.4 3.6 4.2 3 2.8 3.4 3.8 4.2 5.2 5.8 6.2 5.6 3.8 3.6 4.2	1.0646	6.1551	6.0064	0.4429	0.1612

Table 7: Estimated Energy Density Bhubaneswar

Place	**Date**	**Data Set (m/s)**	**K**	**C**	**Vavg (m/s)**	**Vmp (m/s)**	**Energy density (Kwh/m^2/day)**
Bhubaneswar	30th april	2 1.8 2.8 3.2 1.6 4.8 4.2 3.6 4 2.8 5 5.2 5.6 6 6.2 4.6 4.4 5.8	2.0455	4.8932	4.3349	3.5245	0.1079
Bhubaneswar	3rd May	3 2.8 2.2 1.4 2 3.2 2.6 4 4.2 4.6 6.1 5.6 8.4 7.8 3.8 5 4.8 3.6 2.4	1.1423	5.8228	5.5526	0.94	0.1359
Bhubaneswar	4th May	4.2 3.8 2.4 3.4 4 3.2 1.6 2.6 3.8 4.6 5.2 5.6 6.2 5.8 3.6 4.4 3.8	1.0336	6.2931	6.2092	0.229	0.1733
Bhubaneswar	5th May	2.6 4.2 3.8 1.8 2 3.8 2.2 2.4 4 4.4 5.2 6 7.6 9.4 10.2 8 5.8 4.8 6.2	1.383	6.4113	5.8548	2.5339	0.1901

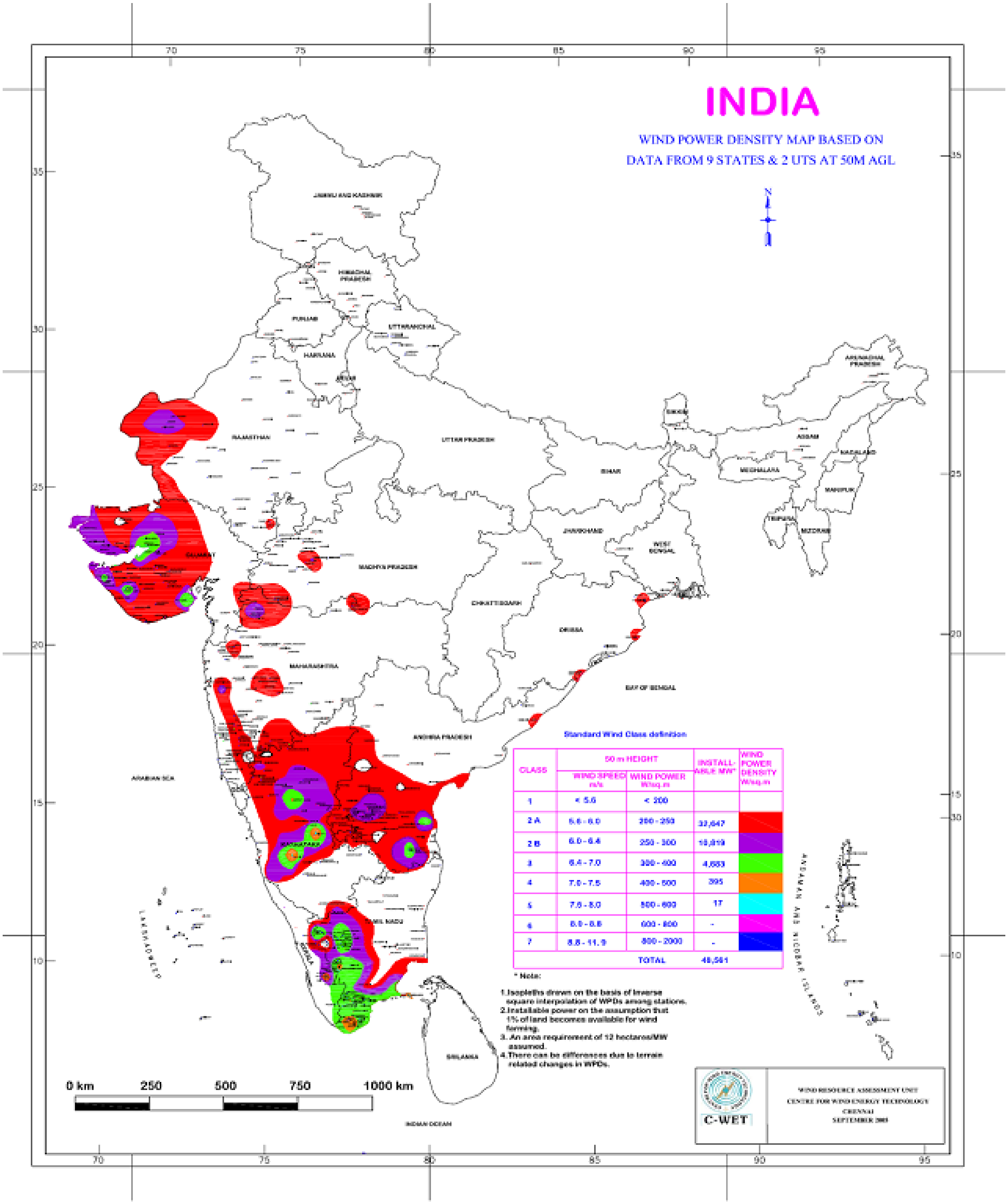


Figure 14: Indian Wind Power Potential

CHAPTER-8

Conclusions

CONCLUSIONS

The potential of wind power generation is immense, a historical source of energy, wind can be used both as a source of electricity and for irrigation and agricultural uses. In today's world, where a greener source of energy is the need of the hour, wind energy is a promising resource, waiting to be harnessed to its true potential. The study of wind turbine and its characteristics showed that how it can be properly designed and used to get the maximum output, even with the variable wind speeds. The development of offshore wind farms, which have both a better energy density and lesser interference with the local systems, is a definite step forward in realization of the wind potential. The Indian scenario is agog with Suzlon making rapid strides, and a lot of multinationals investing heavily.The study of Aggregation technique, being used in the UK, has shown us a path forward towards a realization of an independent wind farm. The analysis of different sites in the country shows how the wind energy density varies from place to place. The following table puts things into perspective regarding the varying energy densities:

Table 8: Comparison of Energy densities

Place	April 30th	May 3rd	May 4th	May 5th	Average
Bhubaneswar	0.1079	0.1359	0.1733	0.1901	0.1518
Chennai	0.1392	0.1131	0.2440	0.1457	0.1605
Delhi	0.1307	0.1985	0.0794	0.1612	0.14245
Mumbai	0.1774	0.0944	0.1141	0.1186	0.126125

All the energy density values are in kWh/m^2/day, from the above table it is clear that the energy density of Chennai being the highest, it makes more sense to setup a wind farm near Chennai than near Mumbai.

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