MEEMPE23 SOLAR ENERGY AND WIND ENERGY

Unit 4 & 5

Unit 4: Wind

Structure - Statistics - Measurements and Data Presentation - Wind Turbine Aerodynamics - Momentum Theories - Basic Aerodynamics - Airfoils and their Characteristics - HAWT-Blade Element Theory - Prandtl's Lifting Line Theory (prescribed wake analysis) - VAWT Aerodynamics - Wind Turbine Loads - Aerodynamic Loads in Steady Operation - Wind Turbulence - Yawed Operation and Tower Shadow.

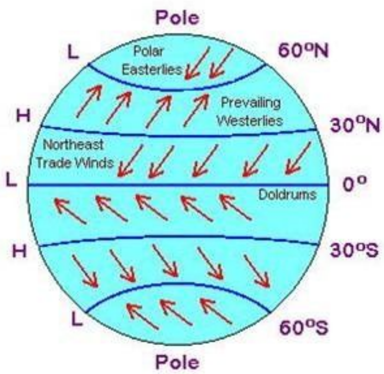
Unit :5 Wind Energy Conversion System (WECS) Siting - Rotor Selection - Annual Energy Output - Horizontal Axis Wind Turbine (HAWT) - Vertical Axis Wind Turbine - Rotor Design Considerations - Number of Blades - Blade Profile - 2/3 Blades and Teetering - Coning - Upwind/Downwind - Power Regulation - Yaw System - Tower - Synchronous and Asynchronous Generators and Loads - Integration of Wind Energy Converters to Electrical Networks - Inverters - Testing of WECS - WECS Control System - Requirements and Strategies - Miscellaneous Topics - Noise etc - Other Applications.

The general atmospheric circulation is large scale **movement of air**. The planetary winds, trade winds, seasonal winds, and local winds forms essential part of this atmospheric circulation. Whereas, the general movement of a **mass of oceanic water** in a definite direction is called as ocean current which is essential for oceanic circulation.

CLASSIFICATION OF WINDS

Planetary Winds:

The winds blowing almost in the same direction throughout year is are called as planetary or permanent winds. In the given diagram **Trade Winds** (North East and South East Trade Winds), **Westerlies** constitutes planetary winds.



Trade Winds:

These winds are part of planetary winds which flows from subtropical high pressure belts to equatorial low pressure belt. These tropical winds have northeasterly direction in the northern hemisphere while they have southeasterly direction in the southern hemisphere.

Seasonal Winds:

The pattern of wind circulation is modified in different seasons due to the shifting of regions of maximum heating, pressure and wind belts. One of the most commonly recognized seasonal winds are the **monsoon** winds.

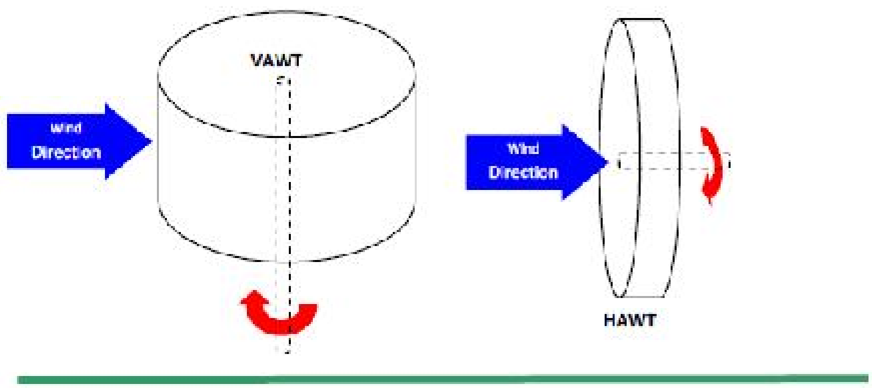
Local Winds:

Local winds have influence over limited geographic area. Land breeze which flows from land to sea at night and sea breeze which flows from sea to land during day time are prominent examples. Other local winds are given below.

For hundreds of years, power was extracted from the wind with ancient designs, known as windmills, designed from wood, cloth and stone to pump water or grind corn. In the 19th century, historical designs, usually massive, heavy and unreliable, were replaced by fossil-fuel engines and a nationally distributed power network was introduced. Since the latter half of the 20th century a greater understanding of aerodynamics and advances since materials, particularly polymers, has led to the return of wind energy extraction. Wind turbines are often used to produce electricity, and are generally called wind turbines.

The shaft and rotational axis orientation specifies the wind turbines first classification. A turbine with a shaft horizontally parallel to the ground is known as a wind turbine or (HAWT) on the horizontal axis. The shaft of a vertical axis wind turbine (VAWT) is normal to the ground (Figure 1).

Figure 1. Alternative configurations for shaft and rotor orientation.



Number	Performance	Horizontal axis	Vertical axis
1	Power generation efficiency	50% - 60%	Above 70%
2	Electromagnetic interference	YES	NO
3	Steering mechanism of the wind	YES	NO
4	Gear box	Above 10KW:YES	NO
5	Blade rotation space	Quite large	Quite small
6	Wind-resistance capability	Weak	Strong (it can resist the typhoon up to 12-14 class)
7	Noise	5-60dB	0-10dB
8	Starting wind speed	High (2.5-5m/s)	Low (1.5-3m/s)
9	Ground projection effects on human beings	Dizziness	No effect
10	Failure rate	High	Low
11	Maintenance	Complicated	Convenient
12	Rotating speed	High	Low
13	Effect on birds	Great	Small
14	Cable stranding problem	YES	NO
15	Power curve	Depressed	Full

Horizontal
VS
Vertical Axis Wind Turbine

Comparison Chart

Horizontal Axis Wind Turbine	Vertical Axis Wind Turbine
The rotating axis of the blades is parallel to the direction of the wind.	The rotating axis of the blades is perpendicular to the direction of the wind.
The main rotor shaft runs horizontally in HAWTs.	The main rotor shaft runs vertically in VAWTs.
HAWTs are generally used under streamline wind conditions where a constant stream and direction of wind is available.	VAWTs are mainly beneficial in areas with turbulent wind flow such as rooftops, coastlines, cityscapes, etc.
The rotor faces the wind stream to capture maximum wind energy.	The rotor can accept wind stream from any direction.
Inspection and maintenance is difficult in HAWT.	Inspection and maintenance is easy.
HAWTs extract more power from wind.	VAWTs extract less power from wind.
They are more efficient than VAWTs.	They are less efficient than HAWTs.
They operate fine in moderate wind speeds.	They can operate even in low wind speeds.

Theoretical Maximum Efficiency

High rotor efficiency is ideal for increased extraction of wind energy, which should be maximized within reasonable production limits. Power (P) transmitted by moving air is measured as a percentage of its kinetic energy (Equation (1)]:

$$P = \frac{1}{2} \rho A V^3 \qquad \begin{array}{l} \rho - \text{Air Density} \\ \text{A} - \text{Swept area} \\ \text{V} = \text{Air Velocity} \end{array} \qquad (1)$$

A physical limit exists to the quantity of energy that can be extracted, which is independent of design. The energy extraction is maintained in a flow process through the reduction of kinetic energy and subsequent velocity of the wind. The magnitude of energy harnessed is a function of the reduction in air speed over the turbine. 100% extraction would imply zero final velocity and therefore zero flow. The zero flow scenario cannot be achieved hence all the winds kinetic energy may not be utilised. This principle is widely accepted and indicates that wind turbine efficiency cannot exceed 59.3%. This parameter is commonly known as the power coefficient *Cp*, where max *Cp* = 0.593 referred to as the Betz limit. The Betz theory assumes constant linear velocity. Therefore, any rotational forces such as wake rotation, turbulence caused by drag or vortex shedding (tip losses) will further reduce the maximum efficiency. Efficiency losses are generally reduced by:

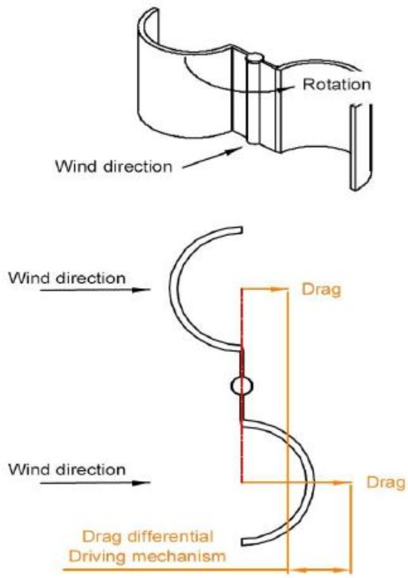
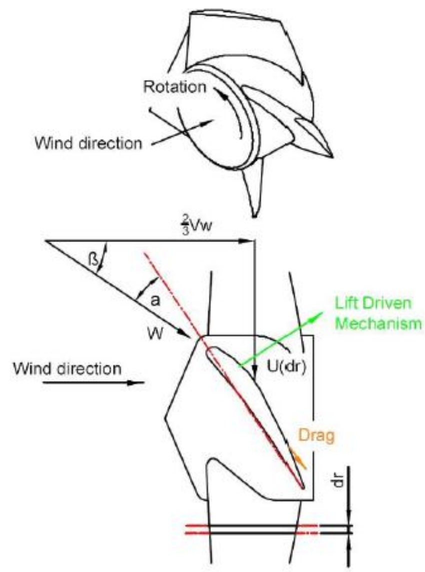
- Avoiding low tip speed ratios which increase wake rotation
- Selecting aerofoils which have a high lift to drag ratio
- Specialised tip geometries

In depth explanation and analysis can be found in the literature [4,6].

Propulsion

The method of propulsion critically affects the maximum achievable efficiency of the rotor. Historically, the most commonly utilised method was drag, by utilising a sail faced normal to the wind, relying on the drag factor (*Cd*) to produce a force in the direction of the prevailing wind. This method proved inefficient as the force and rotation of the sail correspond to the wind direction; therefore, the relative velocity of the wind is reduced as rotor speed increases (Table 1).

Table 1. The two mechanisms of propulsion compared.

Propulsion	*Drag*	*Lift*
Diagram		
Relative Wind Velocity	$= Wind\ velocity - Blade\ velocity$	$= \sqrt{\frac{2}{3} Wind\ velocity^2 + Blade\ velocity(dr)?}$
Maximum Theoretical Efficiency	16% [4]	50% [6]

Practical Efficiency

In practice rotor designs suffer from the accumulation of minor losses resulting from:

- Tip losses
- Wake effects
- Drive train efficiency losses
- Blade shape simplification losses

HAWT Blade Design

A focus is now being made on the HAWT due to its dominance in the wind turbine industry. HAWT are very sensitive to changes in blade profile and design. This section briefly discusses the major parameters that influence the performance of HAWT blades.

Tip Speed Ratio

The tip speed ratio defined as the relationship between rotor blade velocity and relative wind velocity [Equation (2)] is the foremost design parameter around which all other optimum rotor dimensions are calculated:

$$\lambda = \frac{\Omega r}{V_w} \qquad (2)$$

λ – Tip speed ratio
Ω – Rotational velocity (rad/s)
r – Radius
V_w – Windspeed

Aspects such as efficiency, torque, mechanical stress, aerodynamics and noise should be considered in selecting the appropriate tip speed (Table 3). The efficiency of a turbine can be increased with higher tip speeds, although the increase is not significant when considering some penalties such as increased noise, aerodynamic and centrifugal stress (Table 3).

Table 3. Tip speed ratio design considerations.

Tip Speed Ratio	Low	High
Value	Tip speeds of one to two are considered low	Tip Speeds higher than 10 are considered high
Utilisation	traditional wind mills and water pumps	Mainly single or two bladed prototypes
Torque	Increases	Decreases
Efficiency	Decreases significantly below five due to rotational wake created by high torque [4]	Insignificant increases after eight
Centrifugal Stress	Decreases	Increases as a square of rotational velocity [4]
Aerodynamic Stress	Decreases	Increases proportionally with rotational velocity [4]
Area of Solidity	Increases, multiple 20+ blades required	Decreases significantly
Blade Profile	Large	Significantly Narrow
Aerodynamics	Simple	Critical
Noise	Increases to the 6th power approximately [4]	

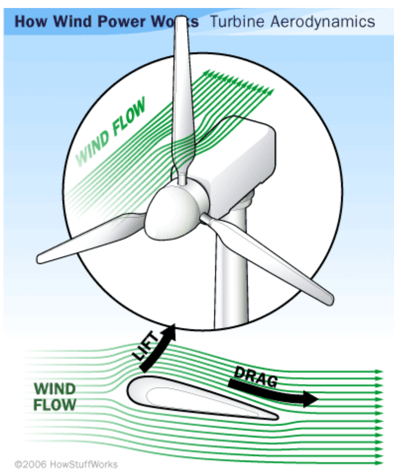
A higher tip speed demands reduced chord widths leading to narrow blade profiles. This can lead to reduced material usage and lower production costs. Although an increase in centrifugal and aerodynamic forces is associated with higher tip speeds. The increased forces signify that difficulties exist with maintaining structural integrity and preventing blade failure.

As the tip speed increases the aerodynamics of the blade design become increasingly critical. A blade which is designed for high relative wind speeds develops minimal torque at lower speeds. This results in a higher cut in speed and difficulty self-starting. A noise increase is also associated with increasing tip speeds as noise increases approximately proportionately to the sixth power. Modern HAWT generally utilise a tip speed ratio of nine to ten for two bladed rotors and six to nine for three blades. This has been found to produce efficient conversion of the winds kinetic energy into electrical power .

Aerodynamics

Aerodynamic performance is fundamental for efficient rotor design. Aerodynamic lift is the force responsible for the power yield generated by the turbine and it is therefore essential to maximize this force using appropriate design. A resistant drag force which opposes the motion of the blade is also generated by friction which must be minimized.

The two primary aerodynamic forces at work in wind-turbine rotors are **lift**, which acts perpendicular to the direction of wind flow; and **drag**, which acts parallel to the direction of wind flow.



It is then apparent that an aerofoil section with a high lift to drag ratio [Equation (4)], typically greater than 30 [20], be chosen for rotor blade design [19]:

$$Lift\ to\ Drag\ Ratio = \frac{Coefficient\ of\ lift}{Coefficient\ of\ drag} = \frac{C_L}{C_D} \qquad (3)$$

The co-efficient for the lift and drag of aerofoils is difficult to predict mathematically. Traditionally aerofoils are tested experimentally with tables correlating lift and drag at given angles of attack and Reynolds numbers [24]. Historically wind turbine aerofoil designs have been borrowed from aircraft technologies with similar Reynolds numbers and section thicknesses suitable for conditions at the blade tip. However, special considerations should be made for the design of wind turbine specific aerofoil profiles due to the differences in operating conditions and mechanical loads.

Angle of Twist

The lift generated by an aerofoil section is a function of the angle of attack to the inflowing air stream The inflow angle of the air stream is dependent on the rotational speed and wind speed velocity at a specified radius. The angle of twist required is dependent upon tip speed ratio and desired aerofoil angle of attack. Generally the aerofoil section at the hub is angled into the wind due to the high ratio of wind speed to blade radial velocity. In contrast the blade tip is likely to be almost normal to the wind.

The total angle of twist in a blade maybe reduced simplifying the blade shape to cut manufacturing costs. However, this may force aerofoil to operate at less than optimum angles of attack where lift to drag ratio is reduced. Such simplifications must be well justified considering the overall loss in turbine performance.

Blade Shape Summary

An efficient rotor blade consists of several aerofoil profiles blended at an angle of twist terminating at a circular flange (Figure 8) It may also include tip geometries for reducing losses. To facilitate production, several simplifications maybe made:

- Reducing the angle of twist.
- Linearization of the chord width.
- Reducing the number of differing aerofoil profiles.

Blade Loads

There are four primary sources of loads that are relevant to horizontal axis wind turbines.

These are

1. aerodynamic loads,

2. gravitational loads,

3. dynamic loads, and

4. control loads.

- Aerodynamic loads include the lift, drag and pitch moment on the rotor such as can be determined by the BEM method.
- Gravitational loads are primarily associated with the weight of the rotor blades.
- This is a cyclic loading whose magnitude on a radial element is

$$dF_g = g\,dm \cos(\psi)$$

- Dynamic loading is the result of changes in the motion of rotor.
  - One example is the centrifugal force generated by the rotation of the rotor.
- Control loads result from continuous changes in blade pitch and torque used to maintain the optimum tip-speed-ratio
  - These control operations can produce intermittent loads on the rotor, shaft and gear box

Fatigue Loading in wind turbines

Because of the complex systems of variable loads that wind turbines are subjected to fatigue damage.

Forces relevant to fatigue are

1. Gravitational force
2. Centrifugal force
3. Wind thrust
4. Other rapidly varying forces arising due to wind turbulence.

Wind Turbine Control Systems:

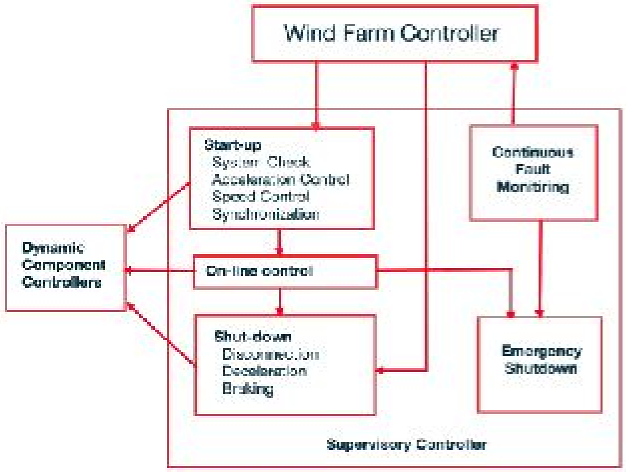
- The control system on a wind turbine is designed to:

1. seek the highest efficiency of operation that maximizes the coefficient of power, Cp,
2. ensure safe operation under all wind conditions.

- Wind turbine control systems are typically divided into three functional elements:

1. the control of groups of wind turbines in a wind farm,
2. the supervising control of each individual wind turbine, and

3. separate dedicated dynamic controllers for different wind turbine sub-systems.



gure 1: Schematic of the wind turbine functional control elements.

- Numerous objectives when controlling a wind turbine:
  - Power Regulation – Would like to get as much energy out of wind turbine as possible.
  - Speed Regulation – Noise restrictions limit the tip speeds of wind turbines to ~80 m/s.
  - Load Mitigation – Ensure that turbine operates safely by limiting the forces.