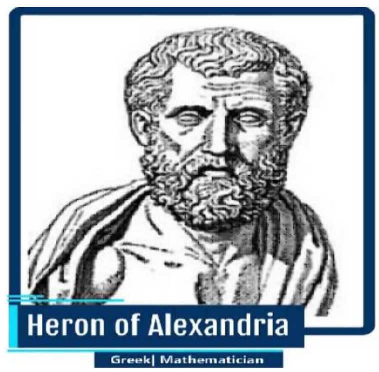
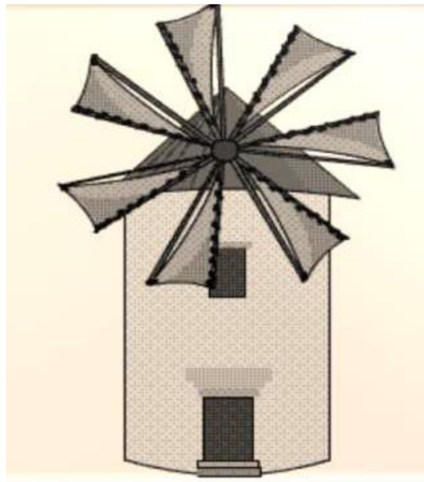
HISTORY OF WIND TURBINES

1. **500 B.C.** The development of sail boats led directly to the development of the first recorded Wind powered device in Persia.
2. Sails were used to drive a mill stone for the grinding of grain. These were seen first in Persia, 500 BC.
3. Some versions were also used to pump water for drinking water and for simple irrigation of agricultural land.
4. 1st century AD: For the first time in known history, a wind-driven wheel is used to power a machine. A Greek engineer, Heron of Alexandria, creates this windwheel. As sails developed, wind power devices became even more powerful.



5. The device shown in below was common around this time

6. In Cyprus and Greece similar machine can be seen, even today.
7. They are still using pump water for agricultural use
8. 1300 - 1850 A.D. This type of windmill design became familiar in Europe between 1300 and 1850 AD. The windmill design is much more like the traditional windmills we see even today. It was designed particularly for the large scale milling of grain



9. 1887: The first known wind turbine used to produce electricity is built in Scotland.The wind turbine is created by Prof James Blyth of Anderson's. "Blyth's 10 m high, cloth-sailed wind turbine was installed. to power the lighting in the cottage, thus making it the first house in the world to have its electricity supplied by wind power. and lighting the main street.
10. The first electricity generating wind turbine was invented by in 1888 cleveland, by Charles F.Bush. The turbine's diameter was 17 meters (50 feet), it had 144 rotor blades made of cedar wood, and it generated about 12 kilowatts (kW)
11. By 1900: Approximately 2,500 windmills with a combined_peak power capacity of 30 megawatts are being used across Denmark for mechanical purposes, such as grinding grains and pumping water
12. 19th Century In the USA wind powered devices like the one shown in the illustration were eveloped to pump the water. These were especially functional in bone-dry areas where deep wells were essential to find drinking water. In the 1800s, the Halladay windmill was very trendy with thousands made.
13. 1931: A vertical-axis wind turbine design called the Darrieus wind turbine is patented by Georges Jean Marie Darrieus, a French aeronautical engineer. This type of wind turbine is still used today, but for more niche applications like on boats, not nearly as widely as horizontal-axis wind turbines.

14. 1931: A horizontal-axis wind turbine similar to the ones we use today is built in Yalta. The wind turbine has 100 kW of capacity, a 32-meter-high tower, and a 32% load factor (which is actually similar to what today's wind turbines get).

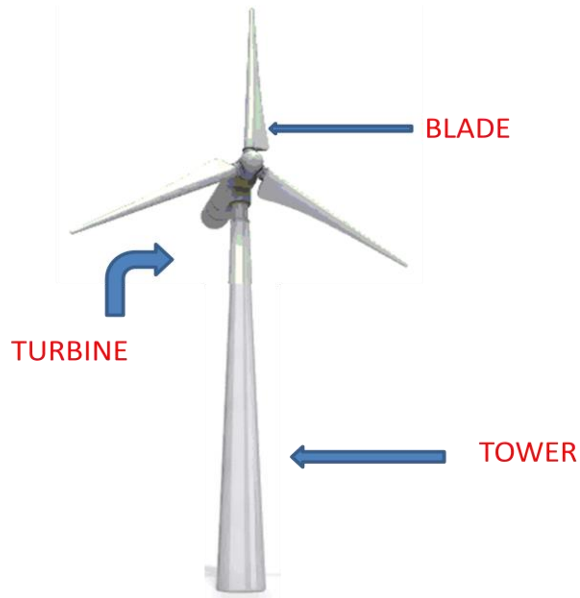
15. 1941: The first megawatt-size wind turbine is connected to a local electrical distribution grid. The 1.25-MW Smith-Putnam wind turbine is erected in Castletown, Vermont. It has blades 75 feet in length.

16. 20th Century (USA) First Use of Wind for Large-Scale Generation of Electricity With the development of electrical power, scientists and technologists developed ways of producing electricity through the use of wind generators (also known as turbines). In the 1930s one of the largest experimental machines, called the Palmer-Putman machine was first used. This was capable of producing 1.25 megawatts of electricity However, due to the materials available at the time, its effectiveness was reduced to a great extent and made the machine hard to maintain. It had 50 meter rotors which were large compared to other designs.

17. **20th Century (Denmark)** After the Second world war the hunt for efficiency wind power generators (turbines) restarted. In Denmark" gedser wind turbine " was created and operated until the mid 1960. This was 20KW machine. The rotor have pitch angle to catch wind more efficient. The main body of the device was build in a similar way to that of the body of an airplane. Airplane technology was applied successfully to the device making more efficient.

Types of windmills

1. Horizontal axis wind turbines



Advantages

a. Tall towers enable accessing stronger winds

b. Blades capture wind energy throughout rotation

Disadvantages

a. a Strong and huge towers required

b. Complexity during construction

c. Need to be turned to face the wind

2) Vertical axis wind turbines

Advantages

a. Generates power independent of wind direction

b. Low cost

c. Strong tower not needed since generator is on the ground

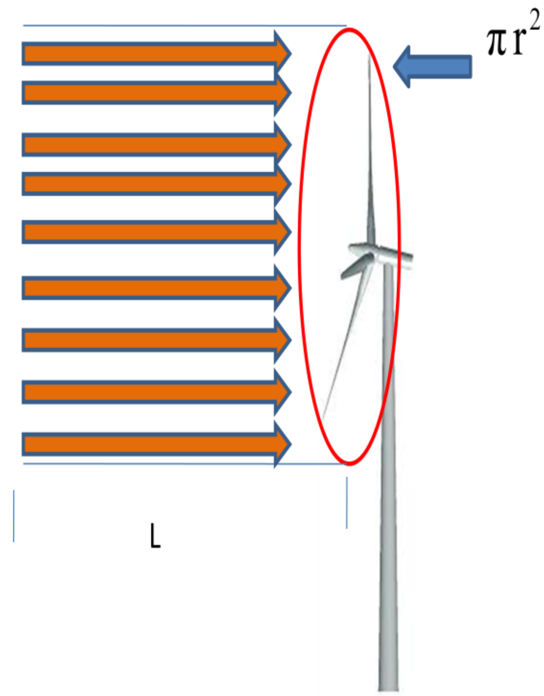
Disadvantages

a. Low efficiency (only one blade works at a time)

b. May need wires to support

c. More turbulent flow near ground

<u>**Power in Wind**</u>



Assume the wind velocity is = v

The kinetic energy of the wind is

$$K.E = \frac{1}{2} m v^2 \text{ ------------------------ (1)}$$

We need to estimate the mass of wind

$$\text{air density} = \rho \ \ Kg/m^3$$

volume of air is going through blades=V m^3

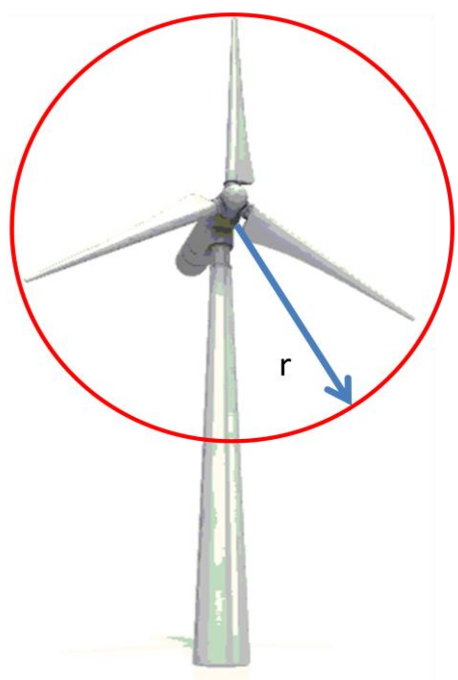
$$\text{mass of the wind (m)} = \rho V \text{ --------- (2)}$$

$$\text{area of the blades circle} = \pi r^2$$

Depth of air is = L

Sub equation (2) in (1)

$$K.E = \frac{1}{2} \rho V v^2 \text{ ---------------------- (3)}$$



We know that volume=area* length

V=A*L ---------------------- (4)

Sub equation (4) in (3)

$$K.E = \frac{1}{2} \rho A L v^2 \text{---------------------- (5)}$$

We know that power is energy unit time i.e $\frac{dE}{dt} = \text{power}$

$$\text{power(p)} = \frac{1}{2} \rho A \frac{dL}{dt} v^2$$

We know that velocity = length/ time

$$\frac{dL}{dt} = \text{velocity}\,(v)$$

$$\text{power}(p) = \frac{1}{2}\rho A v v^2$$

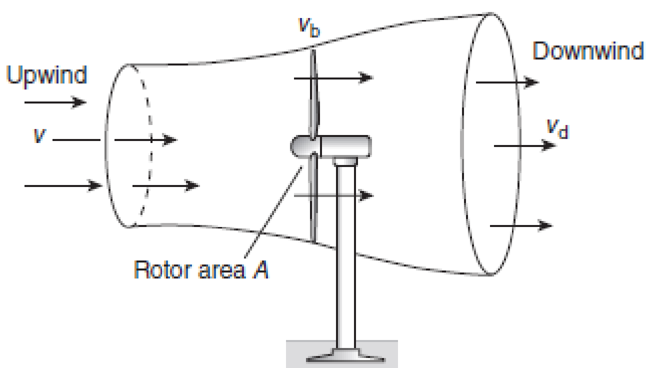
$$\text{power}(p) = \frac{1}{2}\rho A\ v^3$$

$$\text{power}\,\alpha\, v^3$$

Note that the power in the wind increases as the *cube* of wind speed

BETZ LIMIT

The original derivation for the maximum power that a turbine can extract from the wind is credited to a German physicist, Albert Betz, who first formulated the relationship in 1919. The analysis begins by imagining what must happen to the wind as it passes through a wind turbine. As shown in Figure, wind approaching from the left is slowed down as a portion of its kinetic energy is extracted by the turbine. The wind leaving the turbine has a lower velocity and its pressure is reduced, causing the air to expand downwind of the machine



The wind is arrived to the turbine blades are known as upwind.

The wind is leaving from the turbine blades are known as downwind.

The power extracted by the blades per second E_b is equal to the difference in kinetic energy between the upwind and downwind air flows

$$E_b = \frac{1}{2} m_1 (v^2 - v_b^2) \text{--} (1)$$

The mass of the wind striking the blades per second is (m)

$$\frac{m}{t} = \frac{\rho AL}{t} = m_1 \; (\because \text{mass of the wind (m)} = \rho \text{V})$$

$$m_1 = \rho A \frac{L}{t}$$

$$m_1 = \rho A v \text{--} (2)$$

Sub equation (2) in (1)

$$E_b = \frac{1}{2} \rho A v (v^2 - v_b^2) \text{--} (3)$$

Here v is average velocity of winds

$$v = \frac{v + v_d}{2} \text{--} (4)$$

Sub equation (4) in (3)

$$E_b = \frac{1}{2} \rho A \left(\frac{v + v_d}{2} \right) (v^2 - v_b^2) \text{--} (5)$$

Assume

$$\frac{v_d}{v} = \lambda \text{--} (6) \quad v_d = \lambda v$$

Sub equation (6) in (5)

$$E_b = \frac{1}{2}\rho A\left(\frac{v+\lambda v}{2}\right)(v^2 - \lambda^2 v^2)$$

$$= \frac{1}{2}\rho A v\left(\frac{1+\lambda}{2}\right)\left(\frac{1-\lambda^2}{2}\right)v^2$$

$$E_b = \frac{1}{2}\rho A v^3\left(\frac{1+\lambda}{2}\right)(1-\lambda^2)$$

$$E_b = \frac{1}{2}\rho A v^3\left[\frac{1}{2}(1+\lambda)(1-\lambda^2)\right]$$

$$E_b = \underbrace{\frac{1}{2}\rho A v^3}_{\text{Power in wind}}\underbrace{\left[\frac{1}{2}(1+\lambda)(1-\lambda^2)\right]}_{\text{Fraction extracted}}$$

Rotor efficiency (C_p) = $\frac{1}{2}(1+\lambda)(1-\lambda^2)$-- (7)

To find the maximum possible rotor efficiency

$$\frac{dC_p}{dt} = \frac{1}{2}(1+\lambda)(1-\lambda^2) = 0$$

$$= \frac{1}{2}[(1+\lambda)(-2\lambda) + (1+\lambda)(1-\lambda)]$$

$$= \frac{1}{2}(1+\lambda)(1-3\lambda) = 0$$

$$\lambda = \frac{v_d}{v} = \frac{1}{3}$$

now substitute λ = 1/3 into the equation for rotor efficiency

Maximum rotor efficiency $= \frac{1}{2}\left(1+\frac{1}{3}\right)\left(1-\frac{1}{3^2}\right) = \frac{16}{27} = 0.59 \approx 59.3\%$

The maximum theoretical efficiency of a rotor is 59.3%—is called the Betz efficiency or sometimes Betz' law

- Betz law says that, the wind turbine cannot have 100% input to be converted into output.

- The maximum performance that can be attained is 59.3% only.
- In reality, no wind turbine is near to this value. The maximum efficiency that can be attained up to now is in the range of 35 to 40%.
- Therefore, to get better result, we need to understand all the theoretical parameters and redesign our WT to get optimum result.

Losses in wind turbine (WT)

- In general, the losses in the wind turbine occur in the following components
- 1. Gearbox
- 2. Generator
- 3. Turbine blade
- These three parameters define the difference in efficiencies of actual wind turbine from Betz limit.
- 1% to 2% loss is due to slipping of gears in the gear box, 10 to 20% losses occur in generator and rest occurs on turbine blades.

Wind turbine blades design and requirements

- Maximum power from the wind at minimum cost
- The blades tend to be thicker than the aerodynamic optimum close to the root, where stresses due to bending are greatest.
- Compromise between aerodynamic and structural efficiency.
- The choice of material and manufacturing processes

Factors affecting the wind turbine blades

- Tip speed ratio
- No. of blades and its stability and smoothness
- Aerodynamics and structural requirements (lift, drag and gravitational forces)
- Lift/drag ratio
- Minimum wind speed at which turbine blades can rotate

- Wind capturing amount with the blades in order to get the maximum wind energy conversion
- Level from the ground
- Material conditions

Tip speed ratio(TSR)

- The Tip Speed Ratio is of vital importance in the design of wind turbine generators.
- For slow rotation of rotor, wind will pass unperturbed through the gaps between the blades.
- For high rotation of rotor, blades will act as a solid wall for the winds and restrict the flow of wind through it.
- Therefore to get the maximum power from the wind, there should be an optimum speed ratio of the rotor speed and the wind speed.
- This ratio is the Tip Speed Ratio (T.S.R.).

$$\text{Tip speed ratio (TSR)} = \frac{\text{Rotor blade tip speed}}{\text{Upwind wind speed}}$$

Rotor blade tip speed = angular velocity*radius

= ω*R (ω= angular velocity)

= rad/sec*meters

$$\frac{\text{Rotor tip speed}}{\text{Upwind wind speed}} = \frac{RPM * 2\pi \frac{D}{2}}{60 * v}$$

$$\text{Tip speed ratio (TSR)} = \frac{\text{Rotor tip speed}}{\text{Upwind wind speed}} = \frac{\text{rpm} \times \pi \text{D}}{60\text{v}}$$

Where rpm is revolutions per minute for the rotor,

D is the rotor diameter (m), and v is wind speed (m/s) upwind of the turbine.

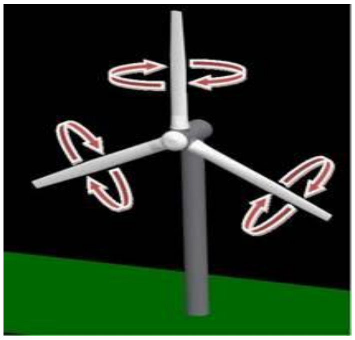
Example: Find the Tip speed ratio of a 20 mph wind is blowing on a wind turbine and the tips of its blades are rotating at 80 mph.

Sol) $\text{Tip speed ratio (TSR)} = \frac{\text{Rotor blade tip speed}}{\text{Upwind wind speed}}$

= 80/20 = 4.

Power Control of Wind Turbines

- Wind turbines are designed to produce electrical energy as cheaply as possible.
- WT are generally designed to yield maximum output at wind speeds around 15 metres per second. (33 mph).
- Its does not pay to design turbines that maximise their output at stronger winds, because such strong winds are rare.
- In case of stronger winds it is necessary to waste part of the excess energy of the wind in order to avoid damaging the wind turbine.
- All wind turbines are designed with some sort of power control and are two different ways of doing this safely on modern wind turbines.
- 1.pitch controlled wind turbine 2.Stall controlled WT
- On a pitch controlled WT the turbine's electronic controller checks the power output of the turbine several times per second.
- When the power output becomes too high, it sends an order to the blade pitch mechanism which immediately pitches (turns) the rotor blades slightly out of the wind. Conversely, the blades are turned back into the wind whenever the wind drops again.
- The rotor blades thus have to be able to turn around their longitudinal axis (to pitch) as shown in the picture



- On a pitch controlled WT, the computer will generally pitch the blades a few degrees every time the wind changes in order to keep the rotor blades at the optimum angle in order to maximise output for all wind speeds.
- The pitch mechanism is usually operated using hydraulics.
- Figure shows a system-level layout of a wind energy conversion system and the signals used. Notice that control is most effective by adjusting pitch angle and controlling the synchronous speed of the generator.

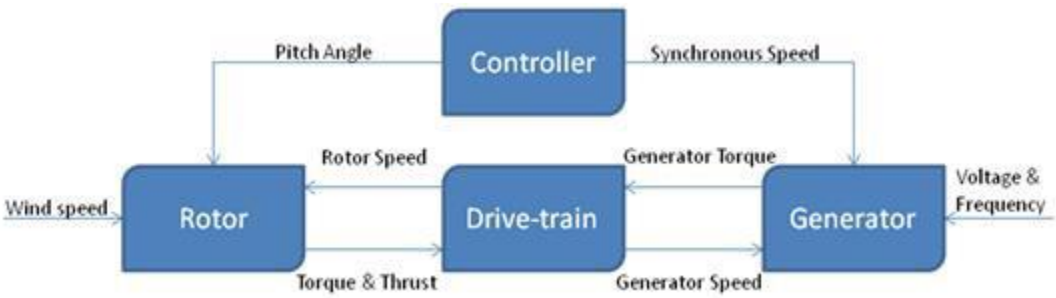


Figure . System-Level Layout of a Wind Energy System

2.Stall Controlled Wind Turbines

- Stall Control Wind Turbine which widely use in wind technology to provide necessary controlling and protection against wind turbine.

<u>The basics of stall control wind turbine</u>

- When the speed of the wind increases up to a certain level where the aerofoil goes into the stall condition.
- In the stall condition, the efficiency of the rotor gets reduce.
- One of the main purposes of the stall control is to stop moving the part in the rotor.
- The stall control is also providing a solution for some complex design problems specialty aerodynamically.
- In this stall controlling method are mainly divided into two methods by controlling approaches such as
- i. Passive power control and
- ii. Active power control

(i)Passive stall power control

- The passive stall control wind turbine system is a simple controlling method by using simple construction.
- passive stall controlled WT uses a simple form of blades are bolted to the hub at a certain fixed angle.
- The rotor airfoil profile is aerodynamically designed such as when the wind speed exceeds a safe limit, the angle of attack of the airfoil to the wind stream is increased , and laminar flow stops and is replaced by turbulence on the top side of the airfoil.
- The lift force on the blade stops acting stalling its rotation.
- In this method, a wind turbine operates at maximum efficiency under low and medium speed and at high wind speed, the wind turbine is controlled by the stalled blade by limiting the rotational speed.
- In this method the blade is slightly twisted along its longitudinal axis. This ensures that the blade stall gradually rather than abruptly as the wind speed reaches its critical stall value.
- So the wind turbine gets protected from the excessive wind speed.
- This controlling method got high reliability against power fluctuations.
- However passive stalled controlling are somewhat cheaper compare with active stall control.
- The advantage of this method is that it avoids the introduction of moving parts into the rotor.
- This advantage is obtained as interplay between the aerodynamic design and the structural design of the airfoil so as to avoid stall induced vibrations.
- Two third of the installed wind turbines are stall controlled.

- However several disadvantages of passive stall controlling method are it required external accessories to start the wind turbine.
- There is large load acting the blade and tower so there is a reliable break for operation is required.
- Due to some of the limitation the active stall controlling method was introduced.

(ii)Active stall power control

- The large wind turbine larger than 1MW rated capacity are equipped with active control mechanisms. in the wind industry.
- Technically the active stall machines resemble pitch controlled machines, since they have pitchable blades. In order to get a reasonably large torque (turning force) at low wind speeds, the machines will usually be programmed to pitch their blades much like a pitch controlled machine at low wind speeds. (Often they use only a few fixed steps depending upon the wind speed).
- When the blade speed is at a higher level it turns in to the stalled condition by using the opposite direction with the pitch control system and this method is known as negative pitch controlling method.
- In this case it increases the angle of attack of the airfoil leading to stall condition ,rather than decreasing the angle of attack to reduce the lift and the rotational speed of the blades.
- This method also maintains the related power at higher wind speed conditions and in this pitch control method also increase the cost of the turbine and also reduce the operation reliability which considers as a disadvantage of such system.
- One of the advantages of active stall is that one can control the power output more accurately than with passive stall, so as to avoid overshooting the rated power of the machine at the beginning of a gust of wind.
- Another advantage is that the machine can be run almost exactly at rated power at all high wind speeds. A normal passive stall controlled wind turbine will usually have a drop in the electrical power output for higher wind speeds, as the rotor blades go into deeper stall.

- In the graphic below, the pitch-regulated turbine is represented by the red curve:
- Stall-regulated wind turbine, their blades designed so that when wind speeds are high, the rotational speed or the aerodynamic torque, and thus the power production, decreases with increasing wind speed above a certain value (usually not the same as the rated wind speed).
- This behavior is illustrate, where a typical stall-regulated turbine is represented by the blue curve.