Renewable Energy Technology

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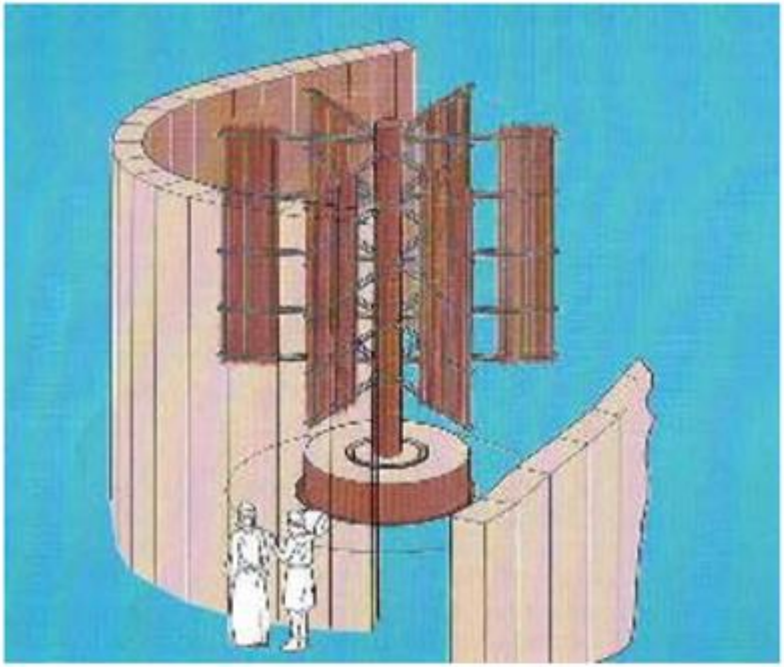
Wind Energy
(Part 1)

Introduction to Wind Energy

Ancient Windmills



Source: www.eurowind-uk.net

- **Used in the Middle Ease, Central Asia and China for milling grain or pumping water.**
- **Date back more than 3000 years.**

Introduction to Wind Energy

Ancient Windmills: Yaw Mechanism

Source: www.molendatabase.nl

Source: www.windmillworld.com

The mill was yawed by hand.

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Further Improvements

- **Windmills grew in size and got further sophistication.**
- **The blade is a wooden frame covered with sail cloth or wooden plates.**

First Attempt for Electricity Generation

Source: www.afm.dtu.dk/wind

Poul la Cour's turbine in 1904, Denmark, used an old-style rotor with a DC generator and was the first one to produce electricity.

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Modern Experiments (1)

The Smith-Putnam turbine in Vermont, USA, 1904, was the first one to introduce proper aero foil blades with a rotor diameter of 53m and to attempt a power out of 1 MW!!

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Modern Experiments (2)

The 200 kW Gedser turbine in Denmark, 1957, with rotor diameter of 24m, showed that further development will be governed mostly by possibility to manufacture better, larger and lighter blades!

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Modern Experiments (3)

The WTS-4 project turbine in USA, 1981, has a generator of 4MW, but the rotor diameter was too small (78m) and the turbine hardly ever operated at its rated capacity.

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To learn from one's mistakes

- **The quest for designing and installing super-large experimental turbines continued in Denmark, USA, Germany, Britain, Italy, Spain, Japan etc.**

- **Valuable experience was gained, many possible failure points and technical hinders identified.**

- **But for the wind-power to enter a commercial breakthrough, some new, reliable, lower cost solutions were required!**

Today's Largest Wind Turbines

1. **Vestas V164 8MW**
2. **Enercon E126 7.5MW**
3. **Samsung S7.0 171 7MW (has largest blade, 85 meters)**

Introduction to Wind Energy

Large modern wind turbines involve all these fields:

Aerodynamic (blades and structures);

Machines (Machine elements, strength of materials, novel materials, testing);

Electrical Engineering (Electrical Machines, grid connection/integration, load management);

Electronics (controls and power electronics);

Controls (Controls and power electronics);

Civil Engineering (Foundations, roads, power lines);

Transport Logistics; Design & Architecture;

Economics; Project Planning & Management …

Wind Turbine Aerodynamics

– *how can we extract energy from the wind ?*

Wind Turbine Aerodynamics

Available Energy in the Wind:

- The kinetic energy of a unit mass of flowing fluid is:

$$E_K = {}^1/_2\, mv^2 \qquad [1]$$

- So the power per unit mass flow would be:

$$P = \dot{E_K} = {}^1/_2\, \dot{m}v^2 \qquad [2]$$

- Using the air density ρ, the flow velocity v and the area A perpendicular to the flow, the mass flow becomes:

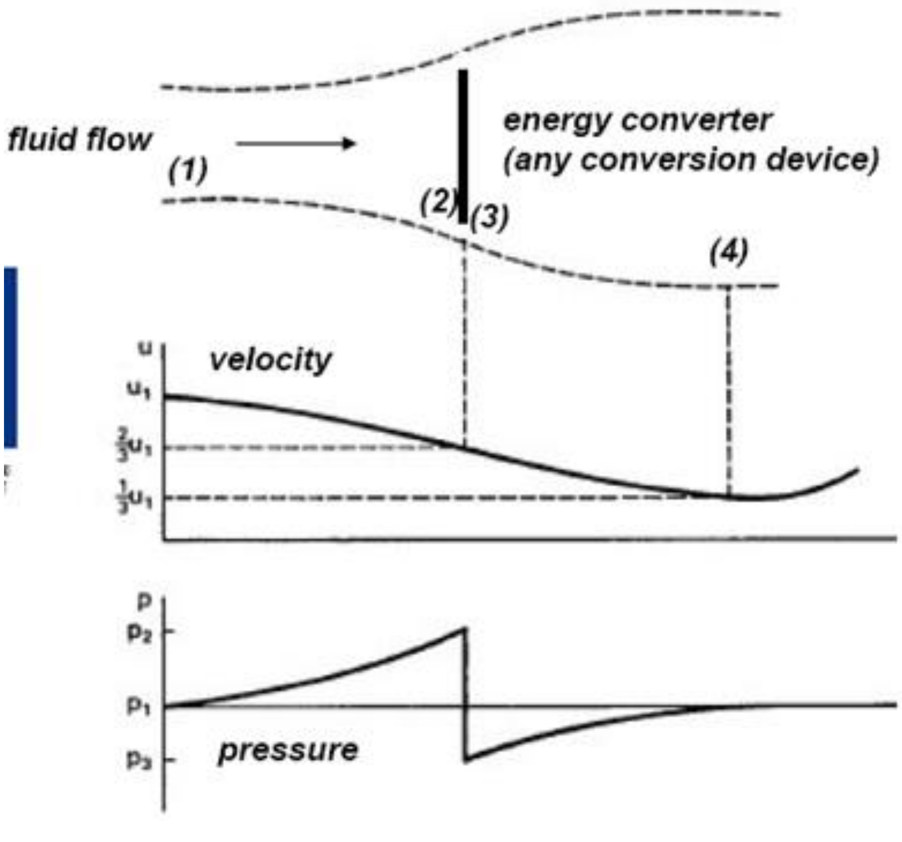
$$\dot{m} = \rho A v \qquad [3]$$

- Then the total available power in the air flow is:

$$P = {}^1/_2\, \rho A v^3 \qquad [4]$$

Wind Turbine Aerodynamics

Flow Through an Energy Converter:



Source: modified from "Wind Energy Systems", Gary L. Johnson

- **Fluid streamlines, velocities and pressure around the energy extraction device:**
  - **Points:**

    (1) Far upstream the rotor

    (2) Just in front of the rotor

    (3) Just after the rotor

    (4) Far downstream the rotor

- **The distance between (2) & (3) is assumed infinitesimal.**

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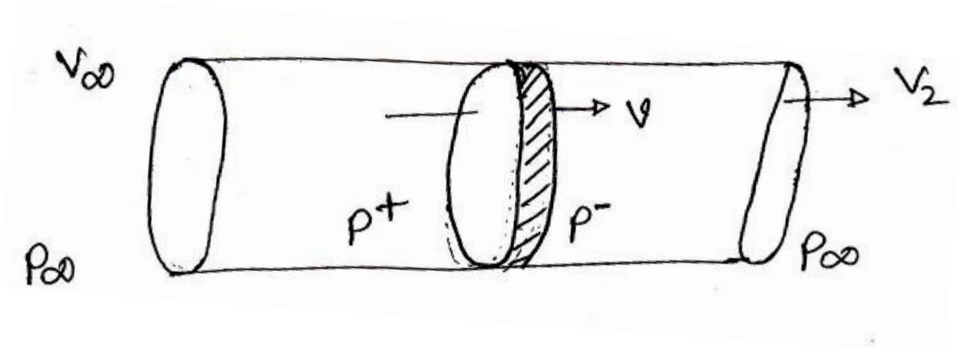
Physical Conditions for Energy Conversion:

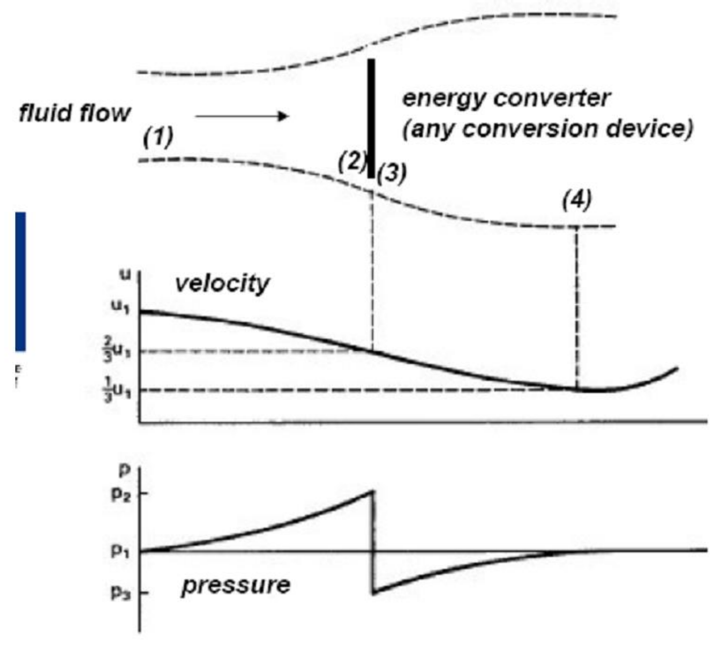
Important Physical Conditions:

- **The fluid velocity falls gradually before and after the energy extraction device and a certain pressure difference builds up across it.**
- **The fluid velocity right across the conversion device does not change $V_2 = V_3$**
- **The pressure far upstream the device and the pressure far downstream are equal to the static pressure of the undisturbed fluid $p_1 = p_4 = p_a$**

Wind Turbine Aerodynamics

BETZ Limit:





Source: modified from "Wind Energy Systems", Gary L. Johnson

According to Bernoulli's Principle,

$$ {}^{1}\!/_{2}\,\rho V_\infty^2 + P_\infty = {}^{1}\!/_{2}\,\rho V^2 + P^+ $$

$$ {}^{1}\!/_{2}\,\rho V_2^2 + P_\infty = {}^{1}\!/_{2}\,\rho V^2 + P^- $$

Subtracting the above two equations,

$$ P^+ - P^- = {}^{1}\!/_{2}\,\rho (V_\infty^2 - V_2^2) $$

Thrust, $T = A(P^+ - P^-) = {}^{1}\!/_{2}\,\rho A (V_\infty^2 - V_2^2)$

Which can also be written in terms of change of momentum, $T = \dot{m}\,(V_\infty - V_2) = \rho A V (V_\infty - V_2)$

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BETZ Limit:

Equating these two trust equation,

$$\frac{1}{2}\rho A(V_\infty^2 - V_2^2) = \rho A V (V_\infty - V_2)$$

$$\frac{1}{2}(V_\infty + V_2) = V$$

V is the velocity when it passes through the wind turbine

Axial Induction Factor or Axial Interference Factor

If we define an Axial Induction Factor "a" , also called "Interference factor", as the fractional decrease in wind velocity between the free stream and the conversion device,

$$a = \frac{V_\infty - V_2}{V_\infty}$$

Then V can be written as, $V = V_\infty(1 - \mathrm{a})$

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BETZ Limit:

So, $P = {}^1/_2\, \rho A V_\infty (1 - \mathrm{a})(V_\infty^2 - V_2^2)$

$$P = {}^1/_2\, \rho A V_\infty^3 [4a - 8a^2 + 4a^3] = {}^1/_2\, \rho A V_\infty^3\, 4\mathrm{a}(1 - a)^2$$

For Maximum Power,

$$\frac{dp}{da} = {}^1/_2\, \rho A V_\infty^3 \frac{d}{da}[4a - 8a^2 + 4a^3] = 0$$

$$\Rightarrow 1 - 4a + 3a^2 = 0$$

$$(\Rightarrow a - 1)(3a - 1) = 0$$

So, a = 1 or a =1/3

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BETZ Limit:

$$P = {}^{1}/_{2}\,\rho A V_{\infty}^{3}[4a - 8a^2 + 4a^3] = {}^{1}/_{2}\,\rho A V_{\infty}^{3}\ 4\mathrm{a}(1-a)^2$$

But when a= 1 then power will be zero, so for maximum power a = 1/3

$$P = {}^{1}/_{2}\,\rho A V_{\infty}^{3}\ 4\left(\frac{1}{3}\right)\left(1-\frac{1}{3}\right)^2$$

$$P = 0.593\ \times P_{wind} = 59.26\%\ of\, P_{wind}$$

$$THIS\ IS\ ALSO\ KNOWN\ AS\ BETZ\ LIMIT$$

Practical Energy Conversion Efficiency of any real device would further be reduced by various aerodynamic losses as well as mechanical and electrical losses.

Wind Turbine Aerodynamics

Power Coefficient (Cp):

$$P = {}^{1}\!/_{2}\,\rho A V_{\infty}^{3}\, 4\mathrm{a}(1-a)^{2}$$

We can now define C_P as the relation between converted power to available power in the fluid flow:

$$C_P = \frac{Rotor\ Power}{Power\ in\ the\ Wind} = \frac{P_{out}}{{}^{1}\!/_{2}\,\rho A V_{\infty}^{3}}$$

The optimum is reached at $a = {}^{1}\!/_{3}$, which leads us to the optimum C_P of $C_{P,\,max} = \frac{16}{27} \approx 0.5926$.

Wind Turbine Aerodynamics

Tip Speed Ratio:

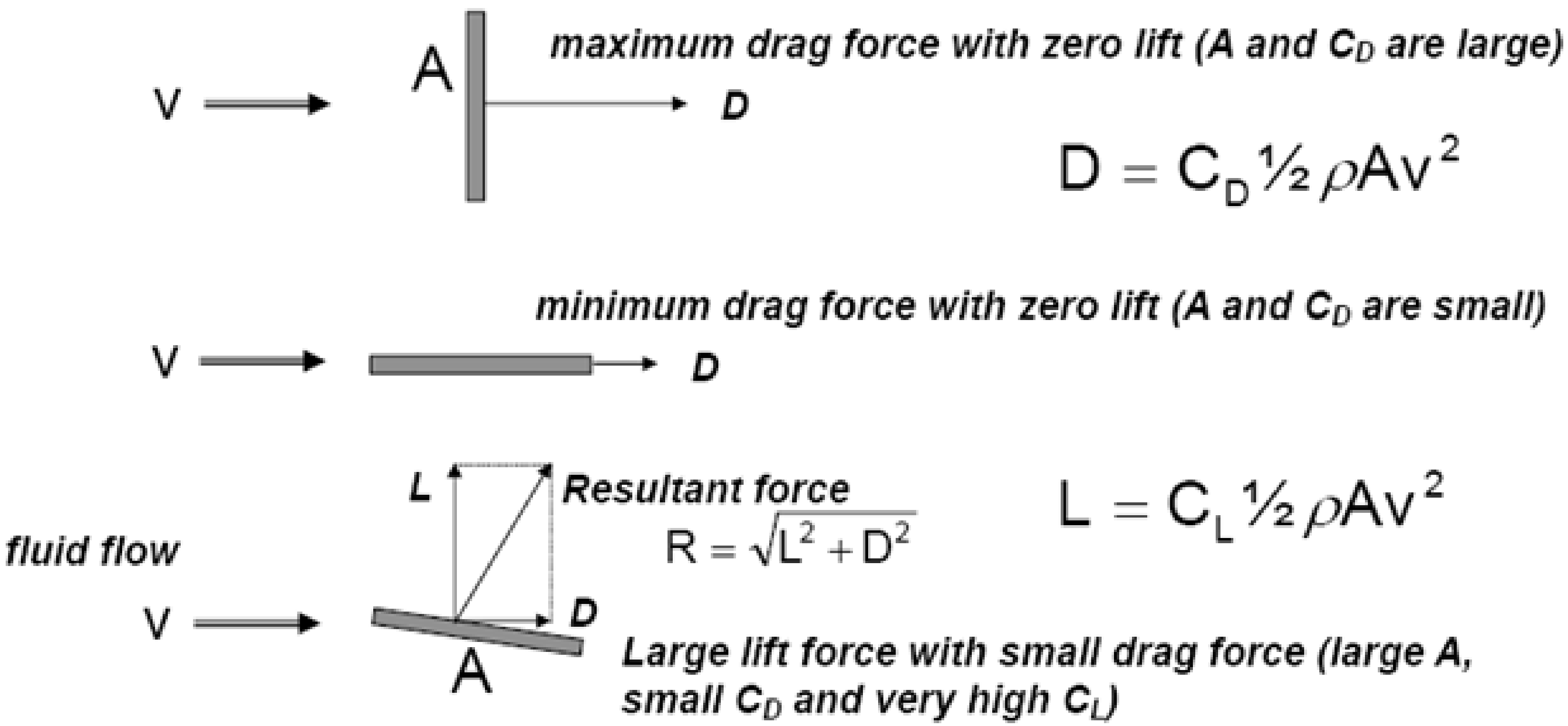
One very important parameter for all types of turbines is the "tip speed ratio", *λ*, which is the ratio of the translational speed at the tip of the turbine blade to the velocity of the free stream of fluid:

$$\lambda = \frac{u}{v_1} = \frac{\Omega R}{v_1}$$

Where u is the blade tip speed and *Ω* and R are the rotational speed and the radius of the turbine rotor respectively.

Lift Force and Drag Force:

Drag and lift forces induced by fluid flowing around a solid structure (the thin flat plate as an example):



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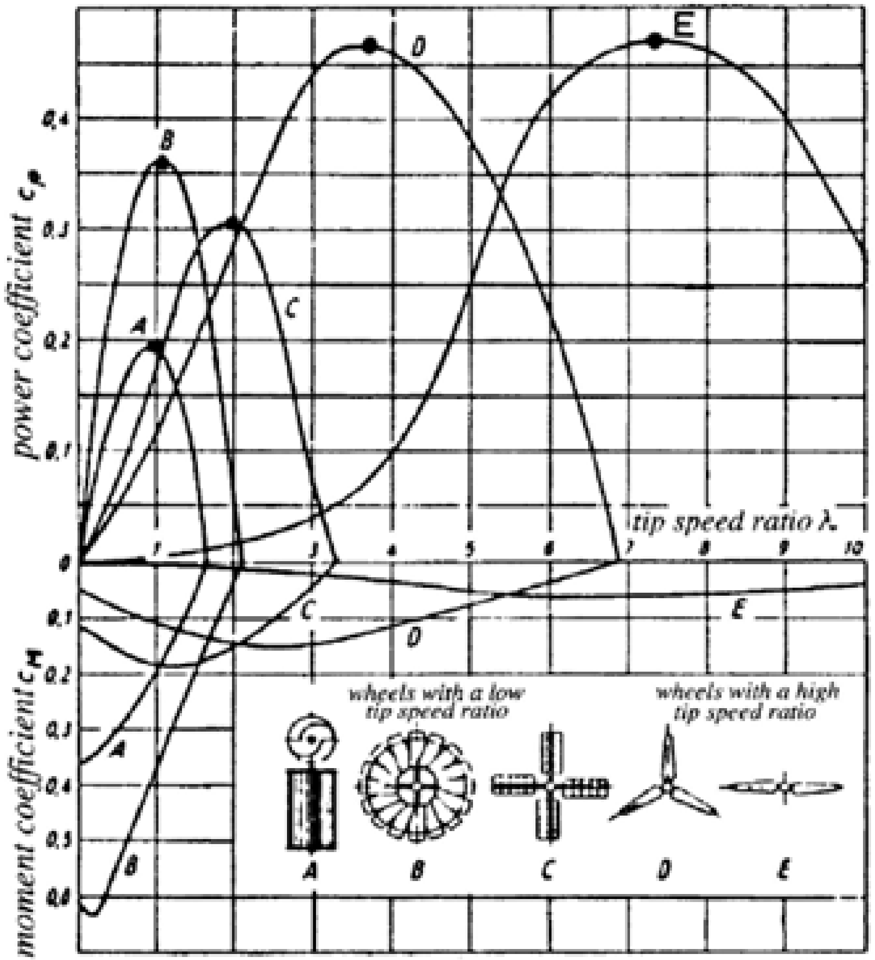


Source: "Wind Power Plants", R. Gasch & J. Twele

Typical variation of power coefficient and moment/ torque coefficient with tip speed ratio for:

A: Savonius rotor

B: Multibladed windpump

C: 4-bladed old mill

D: 3-bladed modern rotor

E: 2-bladed modern rotor

NB: The figure shows only a comparative exemplification, with certain approximations.

Wind Turbine Aerodynamics

Types of Wind Turbines

There are two types of wind machines used today:

- **Horizontal–axis wind machines**
- **Vertical-axis wind machines**

- **Most windmills are the horizontal-axis type.**
- **One wind machine can produce 1.5×10^6 to 4×10^6 kWh of electricity a year.**
- **That is enough electricity for to power 150-400 homes.**

Wind Turbine Aerodynamics

Horizontal-Axis Wind Turbines (HAWTs)

- **Horizontal-axis wind turbines (HAWT) have the main rotor shaft and electrical generator at the top of a tower, and must be pointed into the wind.**
- **Small turbines are pointed by a simple wind vane, while large turbines generally use a wind sensor coupled with a servo motor.**
- **Most have a gearbox, which turns the slow rotation of the blades into a quicker rotation that is more suitable to drive an electrical generator.**

Wind Turbine Aerodynamics

Vertical-Axis Wind Turbines (VAWTs)

- Vertical-axis wind turbines have the main rotor shaft arranged vertically.
- Key advantages of this arrangement are that the turbine does not need to be pointed into the wind to be effective. This is an advantage on sites where the wind direction is highly variable.
- VAWTs can utilize winds from varying directions.
- With a vertical axis, the generator and gearbox can be placed near the ground, so the tower doesn't need to support it, and it is more accessible for maintenance.
- As vertical-axis turbines are difficult to mount on towers hence they are often installed nearer to the base on which they rest, such as the ground or the rooftop of a building.
- The wind speed is slower at a lower altitude, so less wind energy is available for a given size turbine.

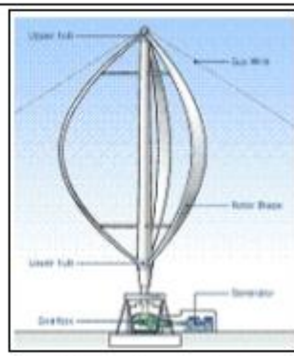
Wind Turbine Aerodynamics

Vertical-Axis Wind Turbines (VAWTs)

Wind Turbine Aerodynamics

Yawing

Vertical Axis Wind Turbines (VAWTs) vs **Horizontal Axis Wind Turbines (HAWTs)**



- Omni-directional
- Always facing the wind
- No yaw mechanism

- Need to yaw as wind changes direction

Wind Turbine Aerodynamics

Starting Torque of a VAWT

- **The lift-force VAWT does not have any starting torque !!**

- **This may be a critical issue for certain applications.**
- **Turbines connected to the electricity grid can use the electric generator as a starting motor.**

- **In stand-alone configurations, either electricity storage devices (again using the generator as a starting motor) or integrated drag-force turbine (as start turbines) can be applied in order for the VAWT to spin up to a point where the lift force can take over.**

A small Darrieus rotor with an integrated Savonius rotor to provide starting torque.

Source: www.oswego.edu/nova/facts/wind

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Disadvantages of VAWTs

- Lower aerodynamic efficiency than HAWTs due to the symmetrical aerofoil blade shape and also because usually the lower part of the turbine spins in the boundary layer of the air flow close to the ground!
- Darrieus rotor require complicated tower support structures or guy wires and have lower coefficients of performance than straight-bladed H-rotors, because only the part of the Darrieus rotor close to its equator operates at optimum tip speed ratio.
- Highly loaded main bearing at the foundation, difficult to repair or replace without dismantling the whole turbine.
- Unpleasant appearance

Wind Turbine Aerodynamics

Advantages of VAWTs

- All main power train components (gearbox, generator, brakes and main bearing) are placed on the ground, allowing for easy access for maintenance and lower stress on the tower.
- Yaw mechanism for facing the wind is not needed – the turbine accepts wind from any direction.
- The blades are easier to manufacture (symmetrical airfoils without any twist or taper).
- All these features result in a simple machine, easily scalable to large dimensions at lower costs than a horizontal axis one.

Future of VAWTs ?

- The main advantage of the VAWT compared to the HAWT is the easier geometrical scalability to larger dimensions.
- HAWTs are difficult to further scale up due to quickly increasing lengths (==masses) of blades and their fatigue loads.
  - For example, the blade for a 1.5 MW HAWT is about 31m long and weighs around 4 to 5 tons.
  - The blade for a 5 MW machine is around 62m long and weighs about 12 to 14 tons, i.e. two times longer but three times heavier.
  - On the design board now is the 100m blade, whose structural integrity is almost impossible unless using new materials.
- VAWTs wouldn't face such problems and may be reinvented when striving towards ever larger turbine dimensions.

Reference

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