Manchester Association of Engineers

Synopsis of talk on “Wind Energy” given by N Jenkins on 16 March 2004

1) Introduction

This technology is emerging as one of the more cost effective of the New Renewables. There are more than 30 GW of wind turbines installed world-wide.
The advantages of wind energy generation are:
(1) Each wind turbine is comparatively large (up to 3 MW),
(2) Once planning permission is obtained, wind farms can be constructed quickly
(3) In high wind speed sites it is low cost (3-4/kWh)
Disadvantages are
(1) Visual impact,
(2) The intermittent energy source
(3) Good wind sites are often remote from load centres

Recently there has been increasing interest in development of offshore wind farms. The reasons for moving offshore are:

- Minimal visual impact
- Higher mean wind speeds
- Lower turbulence

However there will be higher capital and operating costs (typically an increase of costs of 20%).

2) Power from a wind turbine

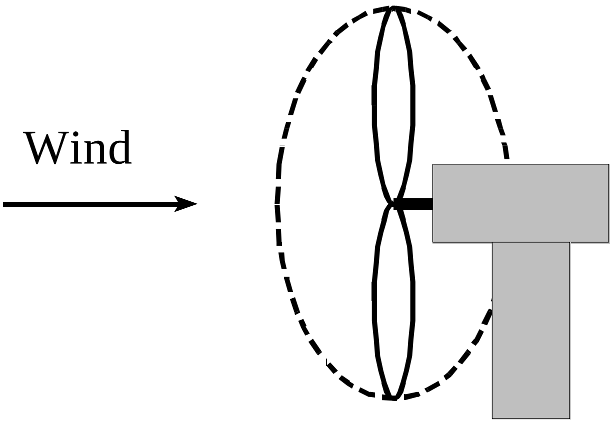


Figure 1 Horizontal axis wind turbine.

Any wind turbine operates by extracting wind energy from across its rotor disk. Presently the preferred design has converged to a three-bladed upwind rotor.

The nacelle houses the gearbox and generator and is rotated into the wind by a yaw mechanism. Power is taken to ground level by pendant cables. Most modern wind turbines are 3-bladed upwind designs.

Power in a fluid flow is given by:

$$P_{air} = 1/2\ \rho A v^3$$

For a wind turbine
ρ: air density 1.225 kg/m^3
A: swept area of rotor
v: free wind speed m/s

However, not all the power can be extracted by the turbine and so a Power Coefficient (Cp) is defined. The power coefficient is simply the ratio of power extracted by the wind turbine rotor to the power available in the wind.

$$Cp = P_{wt}/P_{air}$$

$$P_{wt} = Cp.P_{air} = Cp1/2\ \rho A v^3$$

It can be shown that for any fluid turbine:

$$P_{max} = 8/27 \rho A v^3$$

This leads directly to the Betz limit that

$$Cp_{max} = 16/27 \text{ or } 0.593$$

This means that a turbine can never extract more than 59% of the energy from an air stream.

3) Performance of a wind turbine

It is conventional to define a tip speed ratio (λ)

$$\lambda = \omega R/v$$

ω - rotational speed of rotor
R - radius to tip of rotor
v - free wind speed

Note λ and Cp are dimension-less and so can be used to describe the performance of any size of wind turbine

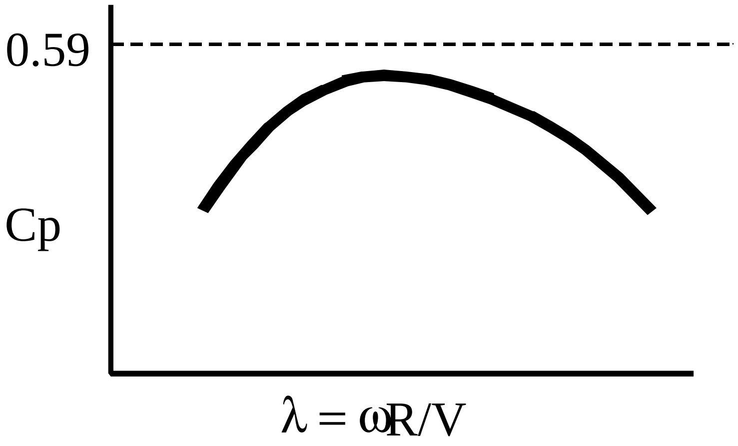


Figure 2 Power Coefficient/Tip speed ratio curve (Cp/λ)

The implications of the Cp/λ curve are that

- For a given speed of rotation only one wind speed gives most efficient operation
- For a given wind speed only one speed of rotation gives most efficient operation
- There may be benefits in designing variable speed operation wind turbines - but care is required with the losses caused by the variable speed equipment.

Because a wind turbine operates by extracting energy from the rotor disk the rotor may be constructed with any number of blades. A rotor with few blades must run with a high rotational speed in order to extract the maximum power from the rotor disk. A 2 bladed rotor has a higher peak Cp as it has less drag. A three-bladed rotor runs more slowly and so develops more torque at a lower speed. Water pumping wind turbines (which require high starting torque) have very large (e.g. 24) numbers of blades.

4) Fixed/Variable speed operation

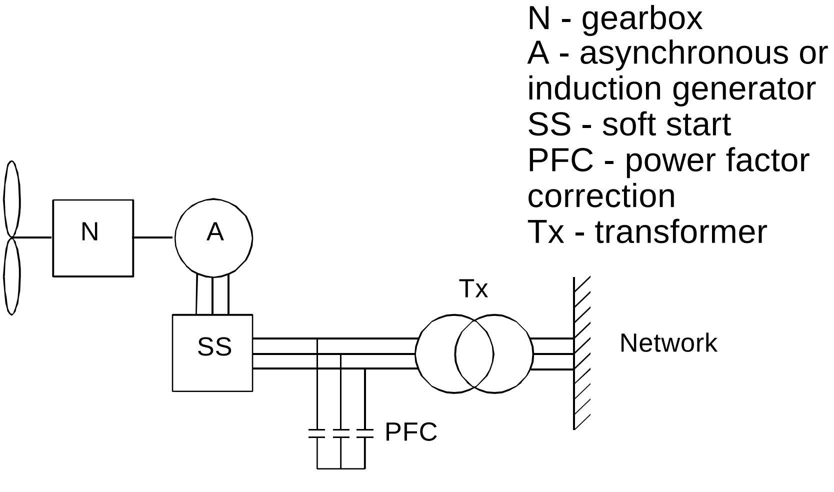


Figure 3 Schematic of fixed speed wind turbines

Fixed speed wind turbines use asynchronous (induction) generators and are coupled to the network through local transformers. The blades are coupled to the generator through a speed increasing gearbox (N). The Power Factor Correction (PFC) capacitors are to improve the power factor of the generator.

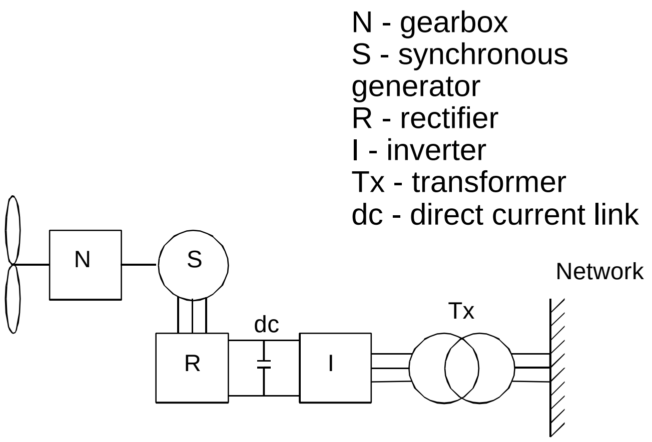


Figure 4 Schematic of variable speed wind turbines

Variable speed wind turbines use power electronic interfaces that allow the speed of the rotor to change and not be locked to the frequency of the network as is the case with fixed speed wind turbines. Modern inverters use Integrated Gate Bipolar Transistors (IGBTs) to give ratings up to 3 MW.

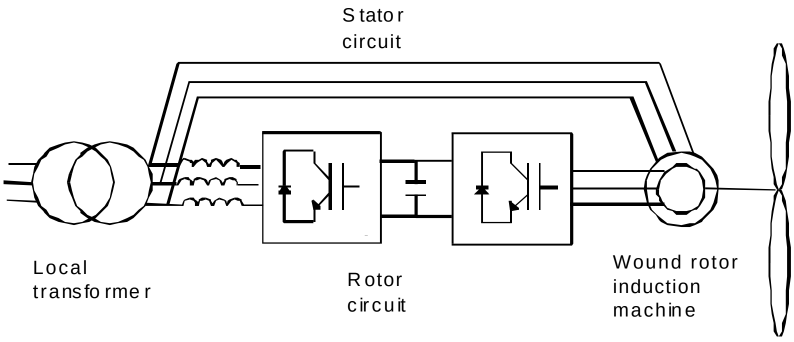


Figure 5 Doubly Fed Induction Generator wind turbine

In order to reduce the size (and hence cost and losses) of the inverters, some variable speed wind turbine operate over a narrower speed range. Theses are known as Douly Fed Induction Generator wind turbine

5) Wind turbine performance

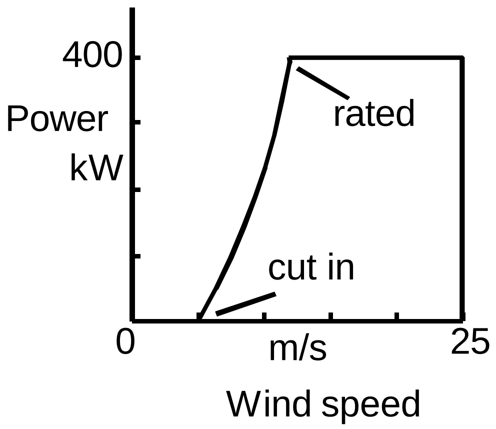
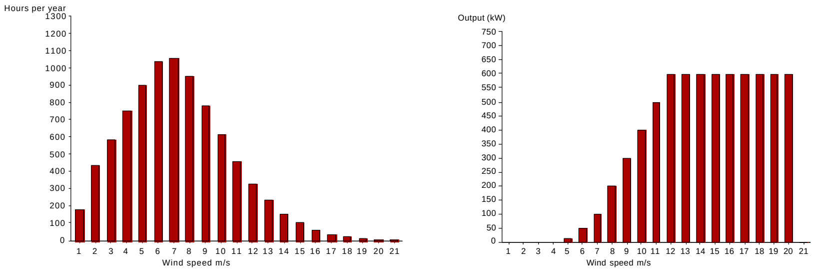


Figure 6 Wind turbine power curve

The performance of a wind turbine is normally described by its power curve. This describes the relationship between wind speed and the output power of the turbine. At cut-in wind speed the turbine starts to generate. At rated wind speed, the power is limited by the turbine rotor. Shut-down (25 m/s) is to protect the structure in very high winds.



Wind speed

Power Curve

Figure 7 Energy output

Annual energy output is calculated by combining the wind speed resource curve with the power curve of the turbine.

$$Energy = \sum_{i=1}^{i=n} H(i)W(i)$$

H(i) – hours per year at wind speed I

W(i) – power output of turbine at wind speed i.

6) Regulation (control) of the generated power

A horizontal wind turbine is a “lift” machine and its blades “fly” in the same way as an aircraft. A lift force is generated perpendicular to the wind velocity and a drag force in parallel to it by the airfoil shape of the turbine blades.

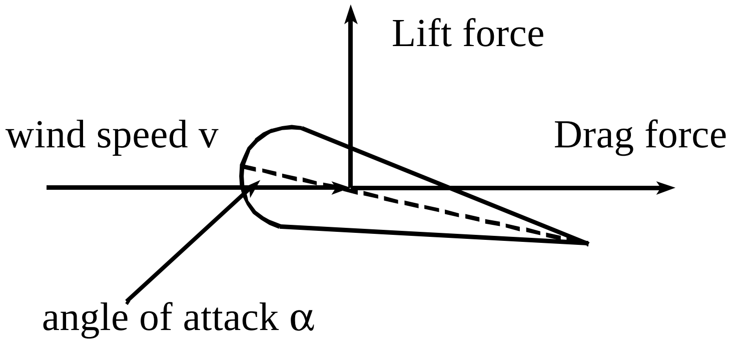
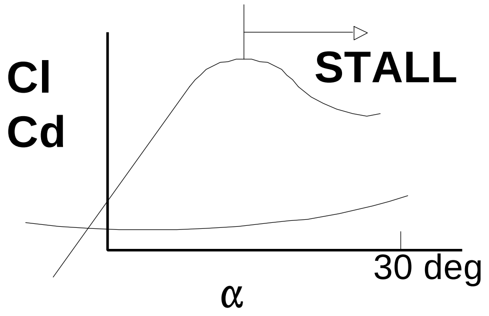


Figure 8 Airfoil section



Lift force = f(Cl)

Drag force = f(Cd)

Figure 9 Airfoil characteristics

The blades use similar airfoil sections to those found on aircraft wings. These sections have well defined characteristics depending on the angle of attack α (or angle of incidence)

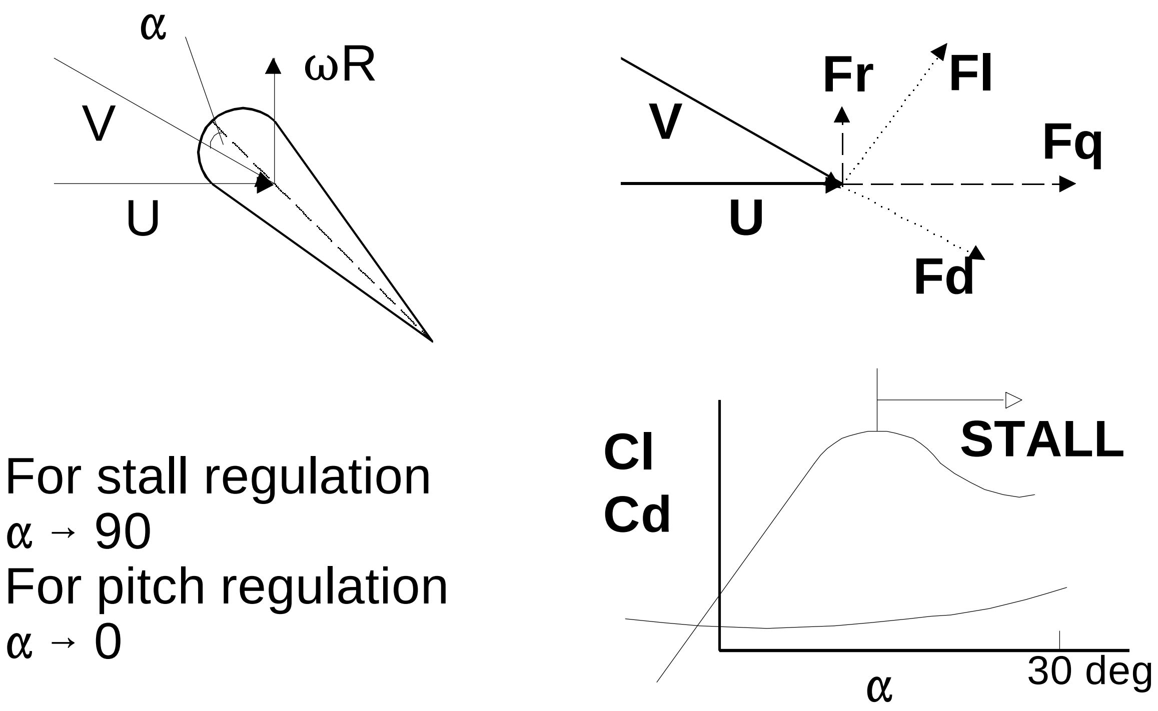


Figure 10 Stall and pitch regulation

For pitch regulation, the blades are rotated mechanically to reduce α and so the lift coefficient and torque on the blades is reduced. For stall regulation the rotational speed of the rotor is held fixed by the generator connected to the network and the angle of attack increases when the free wind speed increases. This results in the blade stalling and the lift coefficient reducing. Both techniques are used to produce the flat portion of the power curve.

7) Mechanical Analogues

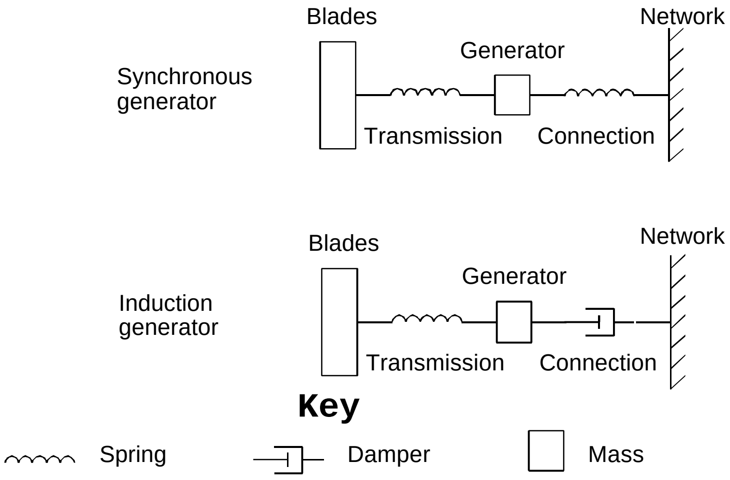


Figure 11 Mechanical analogues of wind turbine drive trains

When a synchronous generator is connected to the power network it acts as a torsional spring. When an induction generator is connected to the network it acts as a torsional damper. As the wind turbine blades pass the tower there is a pulse of torque applied to the rotor, as the apparent wind speed changes. This will excite oscillations in the drive train. It may be seen that with a synchronous generator the drive train will oscillate badly because there is no damping (it is a torsional spring-mass system) while with an induction generator the oscillations will be damped out.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