Wind energy and fundamentals of nuclear energy (472MI-1) (a module of Alternative energy technologies 2) a.y. 2025/26

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C9_5.28

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Content of the module

1) Principles of design of structural elements of an onshore wind power plant: materials, stresses and design of the tower (Prof. M. Gei).

2) Introduction to offshore wind energy (Ing. G. Scherl, formerly at Fincantieri).

3) Nuclear fission. Generations of nuclear power plant. Overview of Gen. II and III. Generation IV technologies and features (Dr. O. Noorikalkhoran, U. of Liverpool).

4) Introduction to nuclear fusion energy systems (Prof. D. Marzullo).

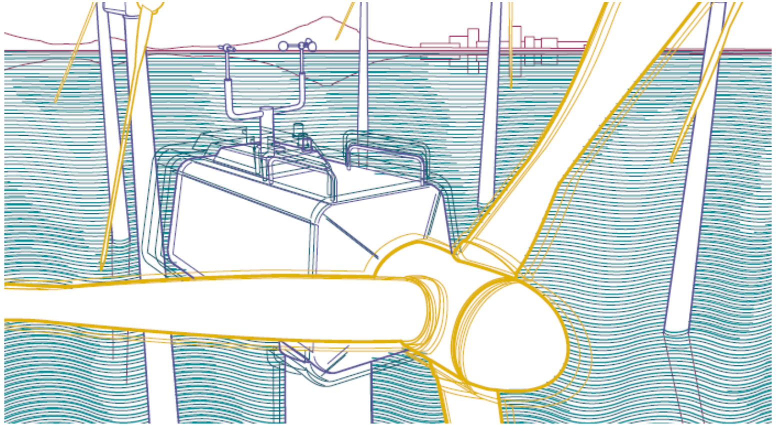
EXAM: written test + non-mandatory assignment regarding a design task of part 1)

Goal of the Part 1): ‘Wind energy’

Introduction to aerogenerators: elements, size, main technical features

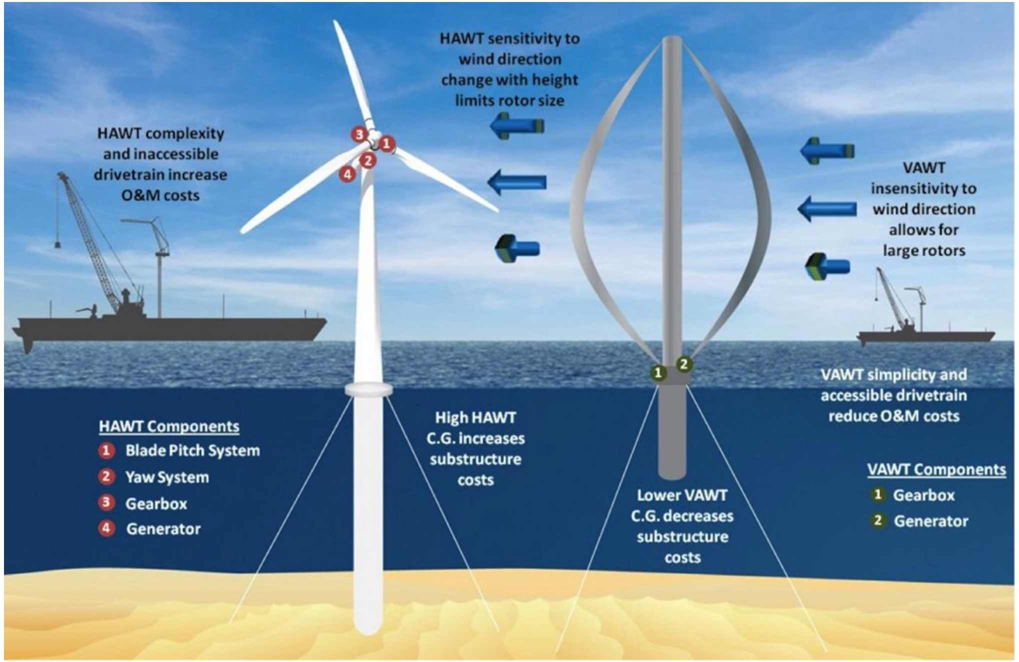
Loading conditions for the design of a supporting tower

Dynamics and preliminary design of a supporting tower



Background

[468MI-2] - RENEWABLE ENERGY TECHNOLOGIES (Prof. Reini)



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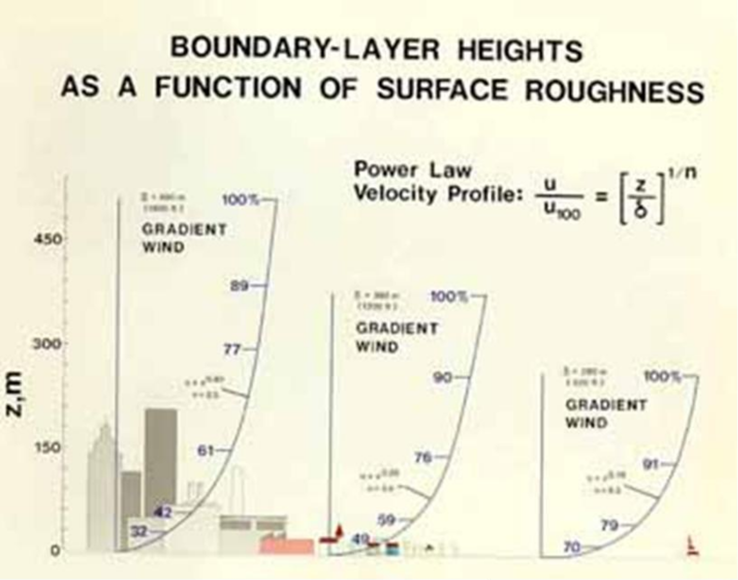
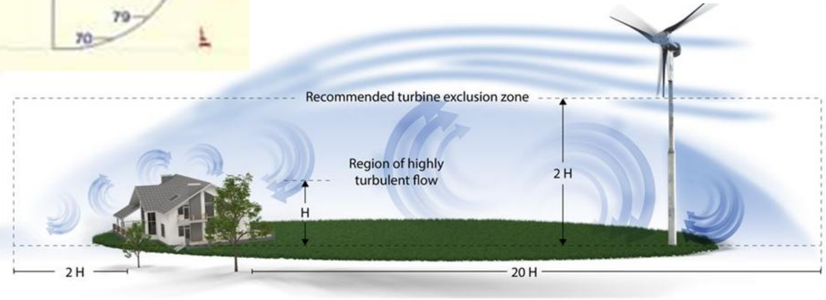


- Flat surfaces are highly favorable for wind energy exploitation
- Horizontal axis wind turbines allow to put the blades where the wind speed is higher
- If some obstacle is present, the turbine has to be placed outside the region of highly turbulent air flow.



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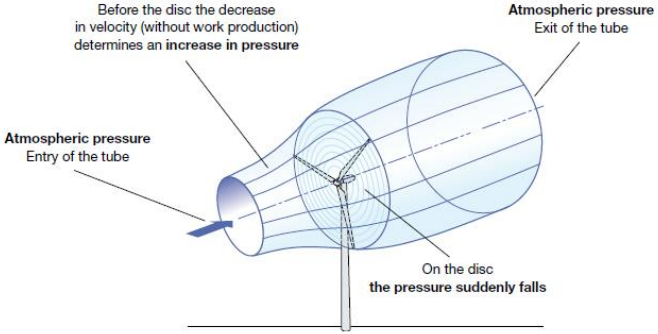
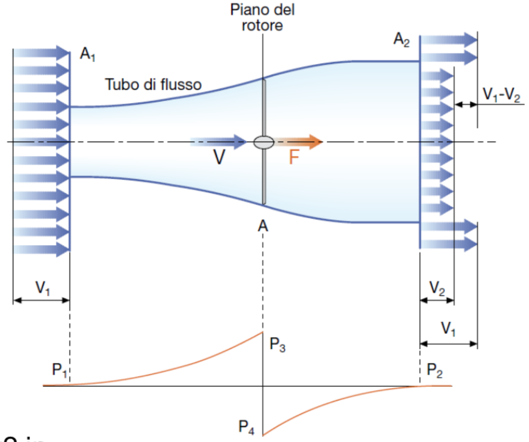
limite di Betz





Velocità nella sezione del disco attuatore:

$$v = \frac{1}{2} \cdot (v_1 + v_2)$$

Il “fattore d’interferenza” è il rapporto:

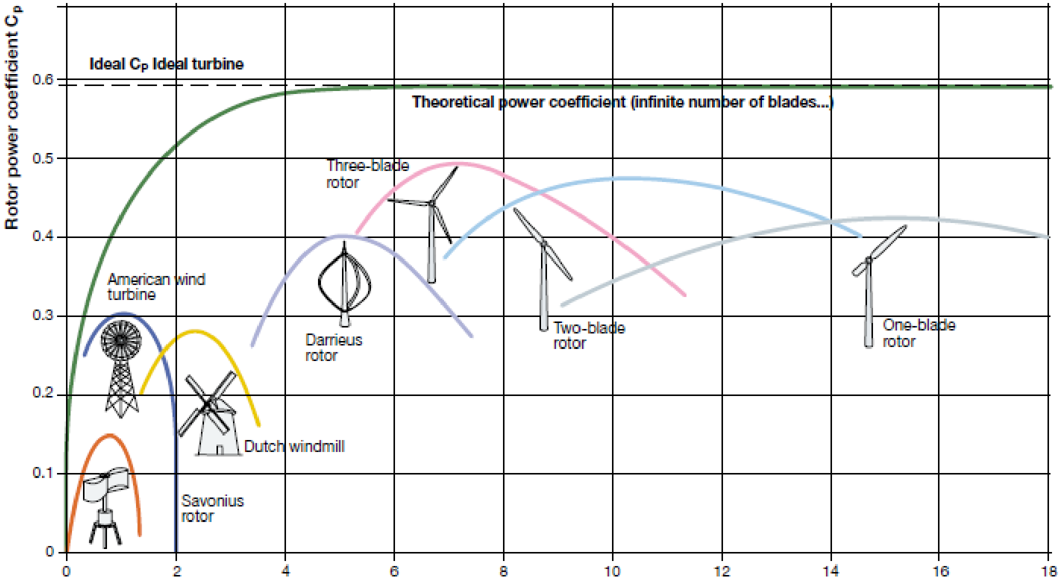
$$a = \frac{v_1 - v}{v_1} = 1 - \frac{v}{v_1}$$

la velocità v sul piano del disco e la velocità v2 in funzione del fattore d’interferenza a e della velocità v1:

$$v = v_1 - a \cdot v_1 = (1 - a) \cdot v_1$$

$$v_2 = 2 \cdot v - v_1 = 2 \cdot (1 - a) \cdot v_1 - v_1 = (1 - 2a) \cdot v_1$$

Background


Rotor power coefficient C_p
Ideal C_p Ideal turbine
Theoretical power coefficient (infinite number of blades...)
Three-blade rotor
Two-blade rotor
One-blade rotor
Darrieus rotor
American wind turbine
Dutch windmill
Savonius rotor
0
0.1
0.2
0.3
0.4
0.5
0.6
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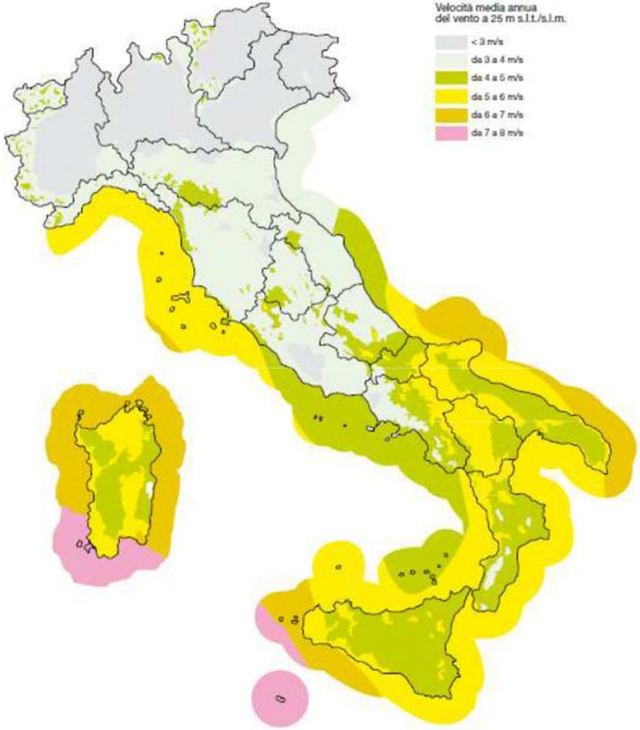
6
8
10
12
14
16
18

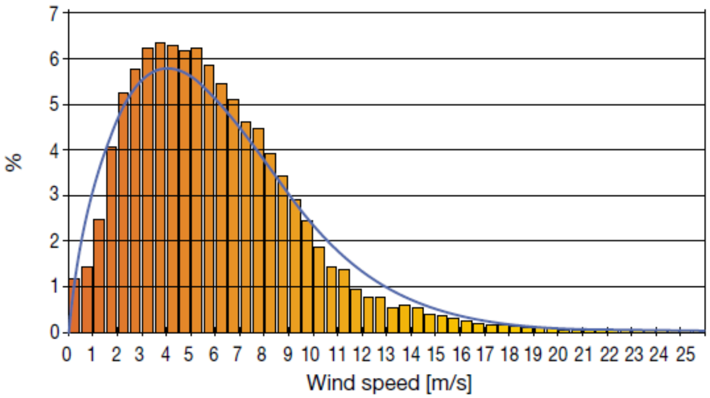
Introduction: the wind resource, Italy data-base



http://atlanteeolico.rse-web.it

Introduction: the wind resource, local data: intensity and direction

Figure 4.3 - Histogram of the occurrence frequency of speed



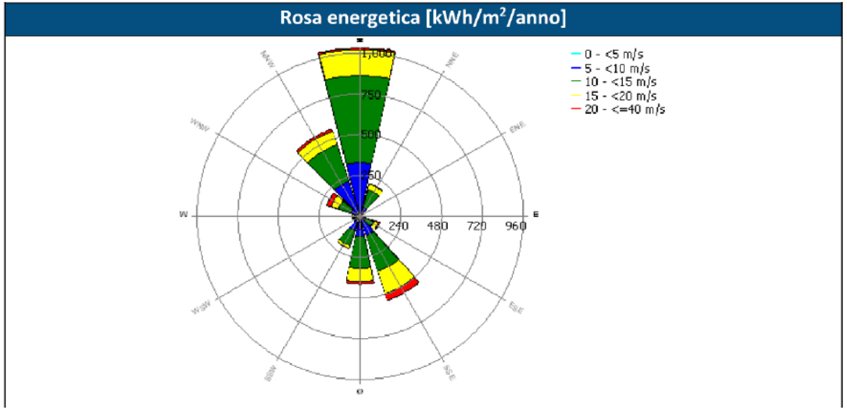
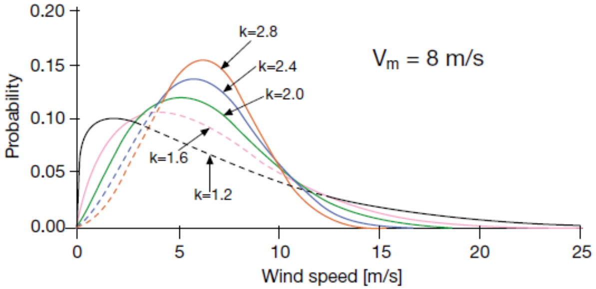

Rosa energetica [kWh/m^2/anno]

Figure 4.4 - Weibull curve for different values of k



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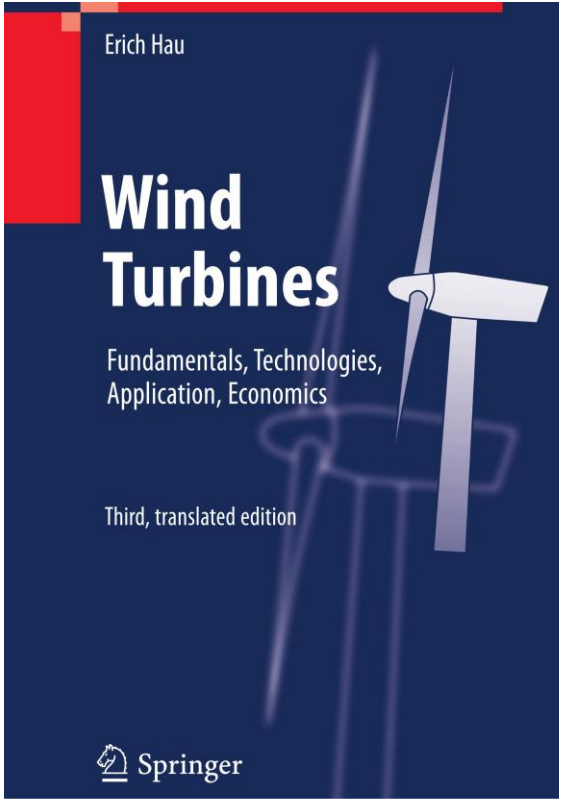
[1] *It is named after the Sweden mathematician Waloddi Weibull who described it in 1951. The probability density function for a given value of scalar velocity v is:*

$$f(v) = \frac{k}{A} \cdot \left(\frac{v}{A}\right)^{k-1} \cdot \exp\left[-\left(\frac{v}{A}\right)^{k}\right]$$

References

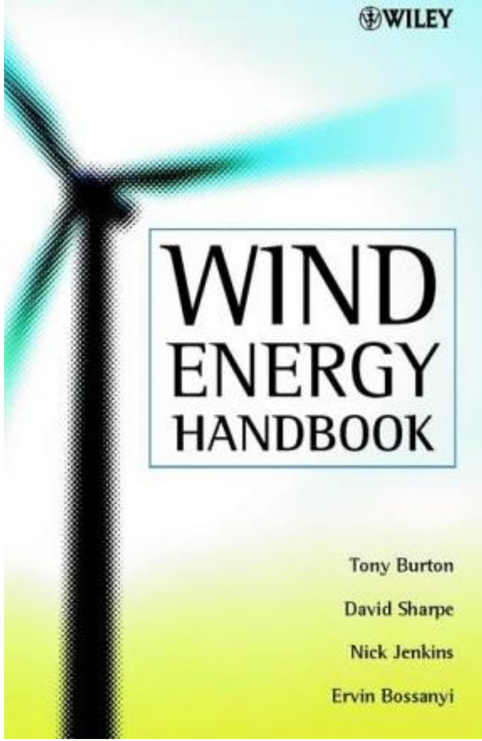

Erich Hau

Wind Turbines

Fundamentals, Technologies, Application, Economics

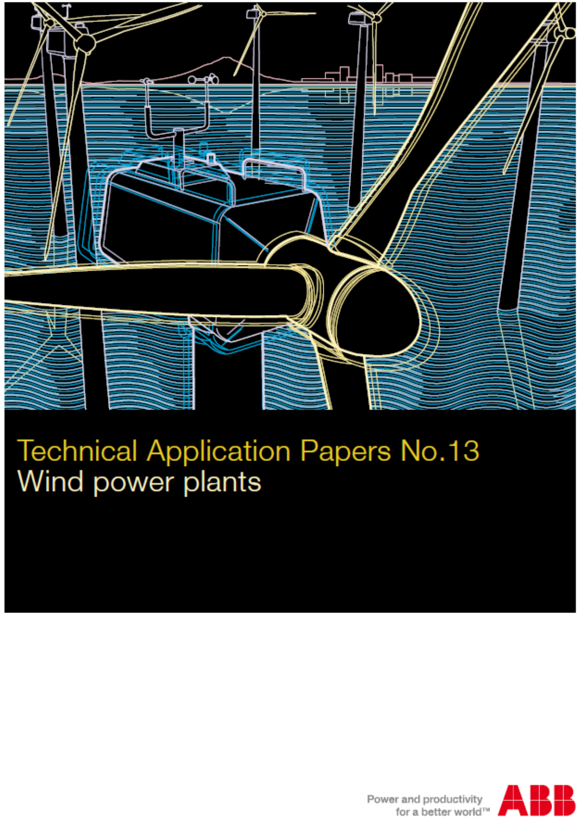
Third, translated edition

Springer


WILEY

WIND ENERGY HANDBOOK

Tony Burton
David Sharpe
Nick Jenkins
Ervin Bossanyi


Technical Application Papers No.13
Wind power plants

Power and productivity for a better world™ ABB

Bigger. Cheaper. Greener.

Vindeby
Year: 1991
Diameter: 35m
Tower Height: 35m
Capacity: 0,45MW

Middelgrund
Year: 2000
Diameter: 76m
Tower Height: 64m
Capacity: 2,00MW

Nysted
Year: 2003
Diameter: 82,4m
Tower Height: 69m
Capacity: 2,30MW

Horns Rev 2
Year: 2009
Diameter: 93m
Tower Height: 68m
Capacity: 2,30MW

Anholt
Year: 2012
Diameter: 120m
Tower Height : 82m
Capacity: 3,60MW

Westermost Rough
Year: 2014
Diameter: 154m
Tower Height: 102m
Capacity: 6,00MW

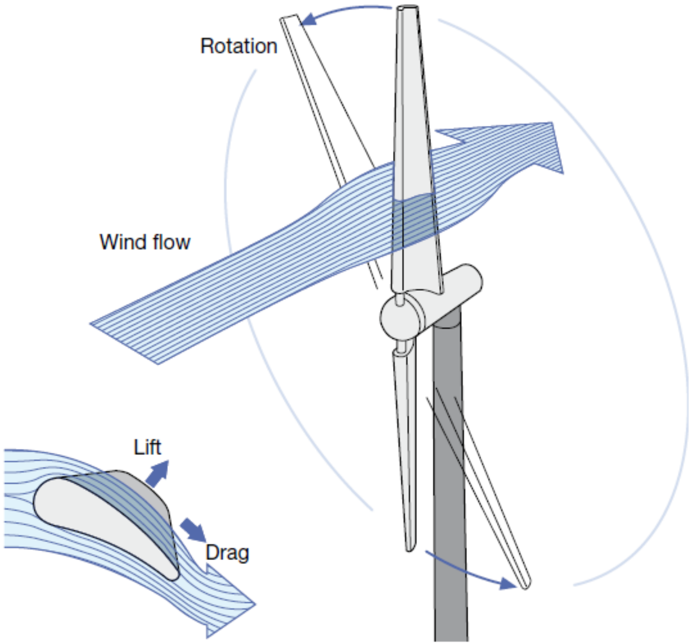
Burbo Bank Extension
Year: 2016
Diameter: 164m
Tower Height: 113m
Capacity: 8,00MW

Introduction

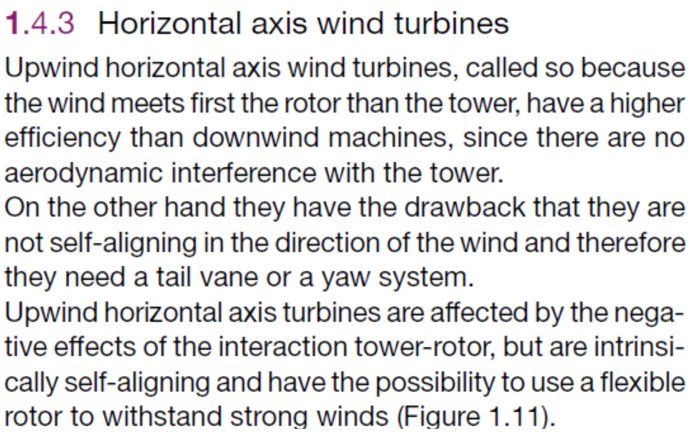
Turbines can be divided into "*lift*" machines and "*drag*" machines according to which force is generated by the wind and exploited as "motive force".

An aerogenerator requires a minimum wind velocity (cut-in speed) of 3-5 m/s and delivers the nameplate capacity at a wind velocity of 12-14 m/s. At high speeds, usually exceeding 25 m/s (cut-off speed) the turbine is blocked by the braking system for safety reasons. The block can be carried out by means of real mechanical brakes which slow down the rotor or, for variable pitch blades, "hiding" the blades from the wind, by putting them in the so-called "flag" position.

Figure 1.7



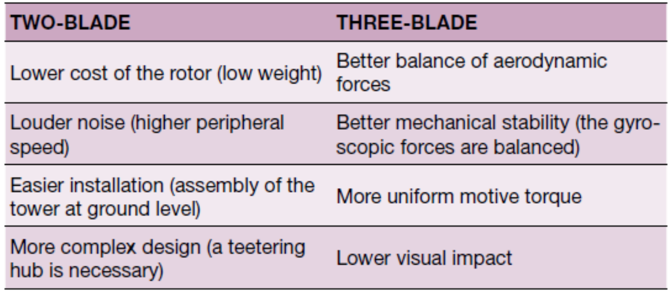
Horizonal axis wind turbines



1.4.3 Horizontal axis wind turbines

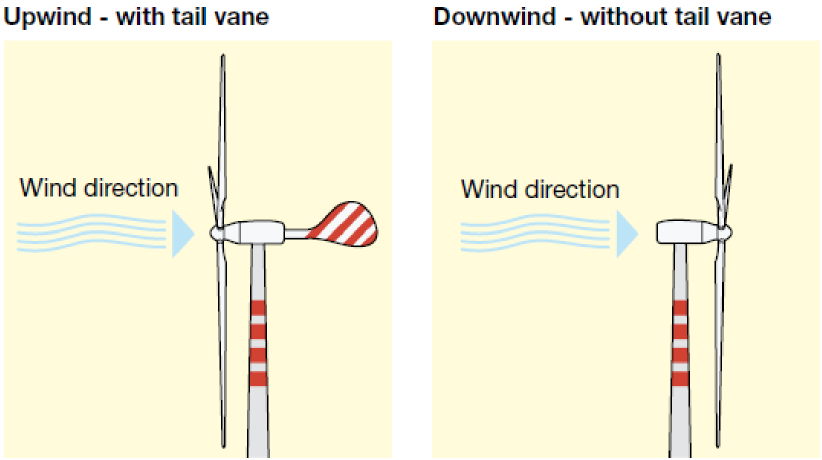
Upwind horizontal axis wind turbines, called so because the wind meets first the rotor than the tower, have a higher efficiency than downwind machines, since there are no aerodynamic interference with the tower.
On the other hand they have the drawback that they are not self-aligning in the direction of the wind and therefore they need a tail vane or a yaw system.
Upwind horizontal axis turbines are affected by the negative effects of the interaction tower-rotor, but are intrinsically self-aligning and have the possibility to use a flexible rotor to withstand strong winds (Figure 1.11).

Table 1.1



TWO-BLADE	THREE-BLADE
Lower cost of the rotor (low weight)	Better balance of aerodynamic forces
Louder noise (higher peripheral speed)	Better mechanical stability (the gyroscopic forces are balanced)
Easier installation (assembly of the tower at ground level)	More uniform motive torque
More complex design (a teetering hub is necessary)	Lower visual impact

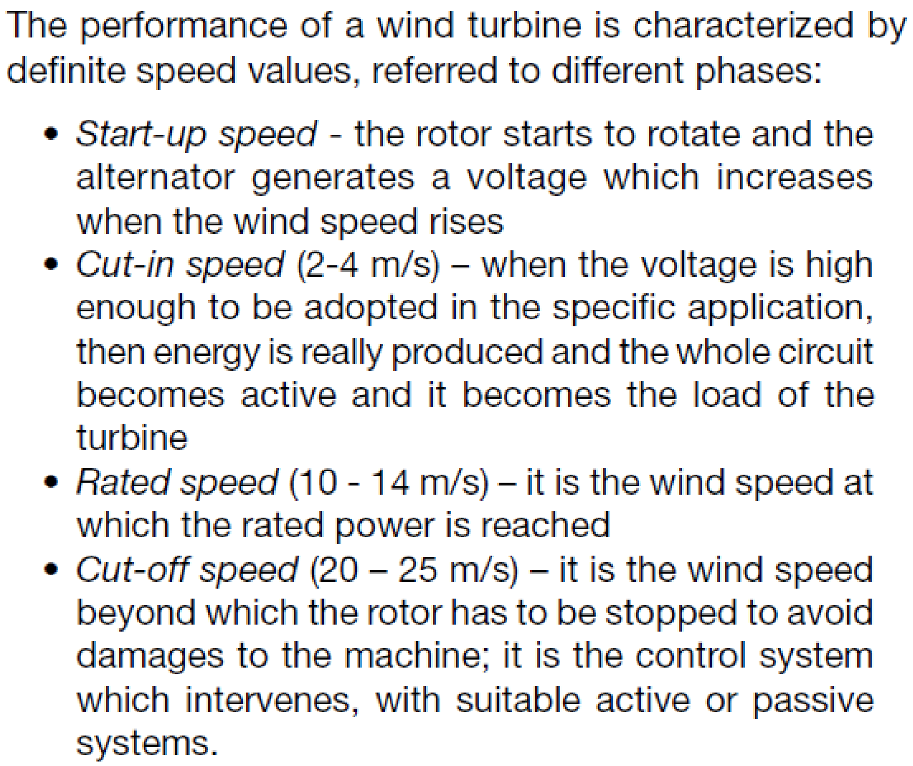
Figure 1.11



Upwind - with tail vane

Downwind - without tail vane

Different definitions of wind speed



The performance of a wind turbine is characterized by definite speed values, referred to different phases:

- *Start-up speed* - the rotor starts to rotate and the alternator generates a voltage which increases when the wind speed rises
- *Cut-in speed* (2-4 m/s) – when the voltage is high enough to be adopted in the specific application, then energy is really produced and the whole circuit becomes active and it becomes the load of the turbine
- *Rated speed* (10 - 14 m/s) – it is the wind speed at which the rated power is reached
- *Cut-off speed* (20 – 25 m/s) – it is the wind speed beyond which the rotor has to be stopped to avoid damages to the machine; it is the control system which intervenes, with suitable active or passive systems.

Wind turbine classes

A wind turbine shall withstand the worst storm which may occur on the installation site, during the design lifetime. If the turbine is installed for 20 years, the extreme gust considered shall be that one having 50-year recurrence period.

Table 1.1 (CEI EN 61400-1) shows the different classes of wind turbines as function of the speed V_{ref}[9] which is the reference wind speed average over 10 min[10].

Table 1.2 - Basic parameters for wind turbine classes

Wind turbine class	**I**	**II**	**III**	**S**
V_{ref} (m/s)	50	42.5	37.5	Values specified by the designer
A I_{ref} (-)	0.16			
B I_{ref} (-)	0.14			
C I_{ref} (-)	0.16			

Where:

- V_{ref} is the reference wind speed average over 10 min
- A designates the category for higher turbulence characteristics
- B designates the category for medium turbulence characteristics
- C designates the category for lower turbulence characteristics
- I_{ref} is the expected value of the turbulence intensity at 15 m/s.

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[9] *A wind turbine designed for a class with reference wind speed V_{ref} is sized to withstand climates for which the extreme value of the mean wind speed over a 10 min time, at the height of the hub of the wind turbine and a recurrence period of 50 years, is lower or equal to V_{ref}*

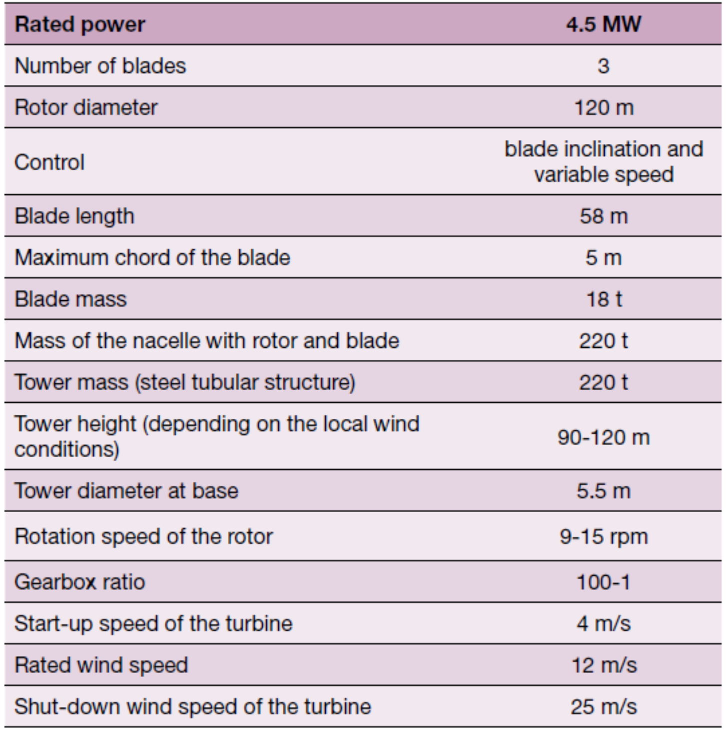
[10] *The Std. IEC 61400-1 defines a further class of wind turbines, class S, to be adopted either when the designer and/or the customer signal special wind conditions or other special external conditions, or when a special safety class is required.*

Features of wind turbines

The main options in a wind turbine design and construction include:

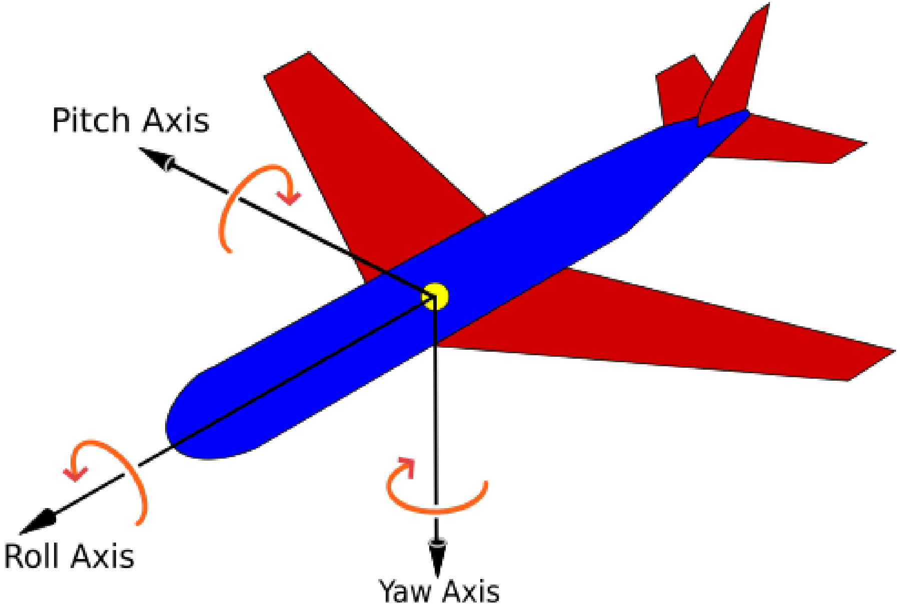
- number of blades (commonly two or three)
- rotor orientation (upwind or downwind of tower)
- blade material, construction method, and profile
- hub design: rigid, teetering or hinged
- power control via aerodynamic control (stall control) or variable-pitch blades (pitch control);
- fixed or variable rotor speed
- orientation by self-aligning action (free yaw) or direct control (active yaw)
- synchronous or asynchronous generator (with squirrel-cage rotor or wound rotor -Doubly Fed Induction Generator (DFIG))
- with gearbox or direct drive generator.

Table 1.3 – Example of features of a wind turbine



Rated power	**4.5 MW**
Number of blades	3
Rotor diameter	120 m
Control	blade inclination and variable speed
Blade length	58 m
Maximum chord of the blade	5 m
Blade mass	18 t
Mass of the nacelle with rotor and blade	220 t
Tower mass (steel tubular structure)	220 t
Tower height (depending on the local wind conditions)	90-120 m
Tower diameter at base	5.5 m
Rotation speed of the rotor	9-15 rpm
Gearbox ratio	100-1
Start-up speed of the turbine	4 m/s
Rated wind speed	12 m/s
Shut-down wind speed of the turbine	25 m/s

A note on 'rotations'

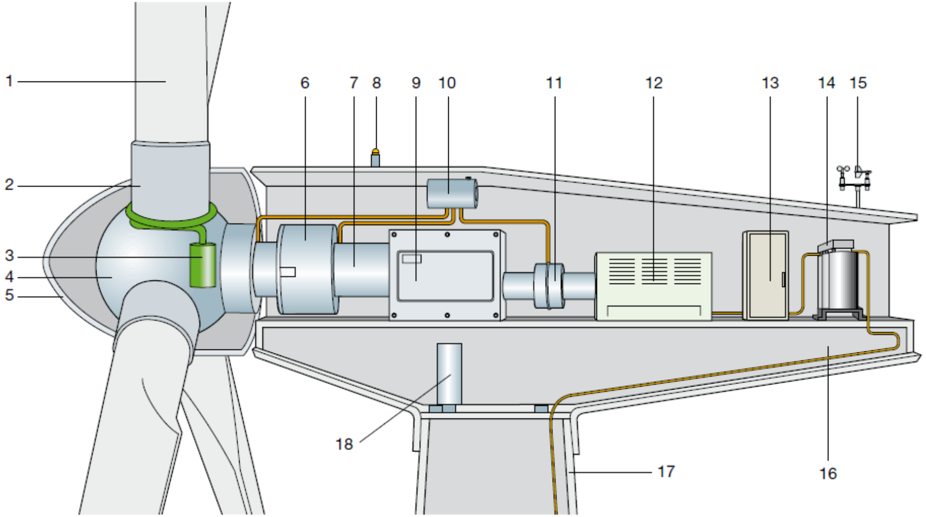


Components of a horizontal axis wind turbine

To summarize, the main components constituting horizontal axis wind turbines are (see Figure 2.1):

1. blade
2. blade support
3. Pitch angle actuator
4. hub
5. spinner
6. main support
7. main shaft
8. aircraft warning lights
9. gearbox
10. mechanical brakes
11. hydraulic cooling devices
12. generator
13. power converter and electrical control, protection and disconnection devices
14. anemometers
15. transformer
16. frame of the nacelle
17. supporting tower
18. yaw driving device

Figure 2.1

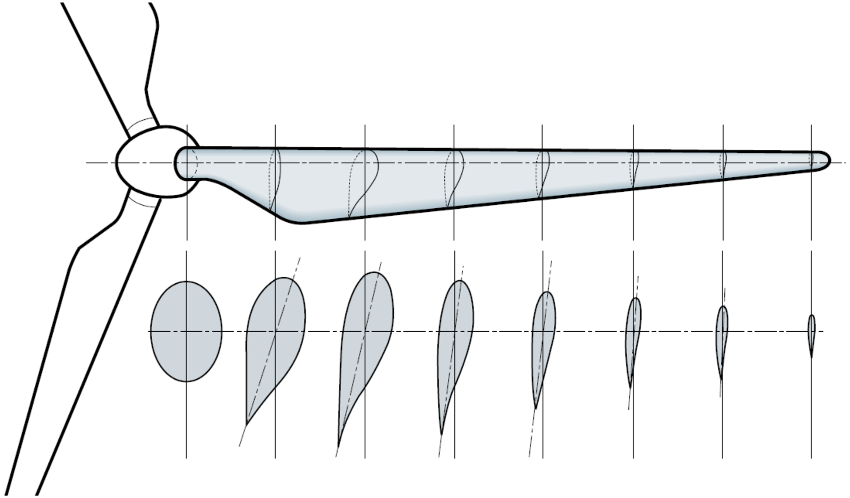


Blades

Since the aerodynamic forces are proportional to the square of the relative speed, they increase rapidly with the distance from the hub; therefore it is important to design the part of the blade near the root so that there is a good lift and a low aerodynamic resistance.

The cross sectional area of the blade is quite large to get the high stiffness necessary to withstand the variable mechanical loads present under normal operation which contribute to determine the wear and tear of the blade. In fact, the wind exerts an unsteady force, both for the fluctuations due to the turbulence, as well as for the higher speed as a function of altitude.

Figure 2.3



Blades

Blades are made from light materials, such as fiber-reinforced plastic materials, which have good properties of resistance to wear and tear.

Fibers are generally made of glass or aluminum for the blades of small and medium size wind turbines, whereas for larger blades carbon fibers are used in the parts subject to more critical loads.

The fibers are incorporated in a matrix of polyester, epoxy resin or vinyl ester constituting two shells kept together and reinforced by an internal matrix.

The external surface of the blade is covered with a layer of colored gel to prevent ageing of composite material due to ultraviolet radiation.

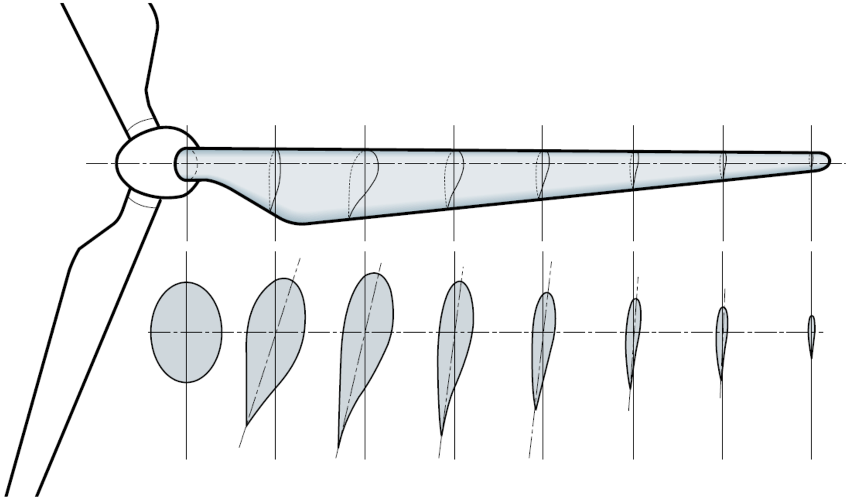


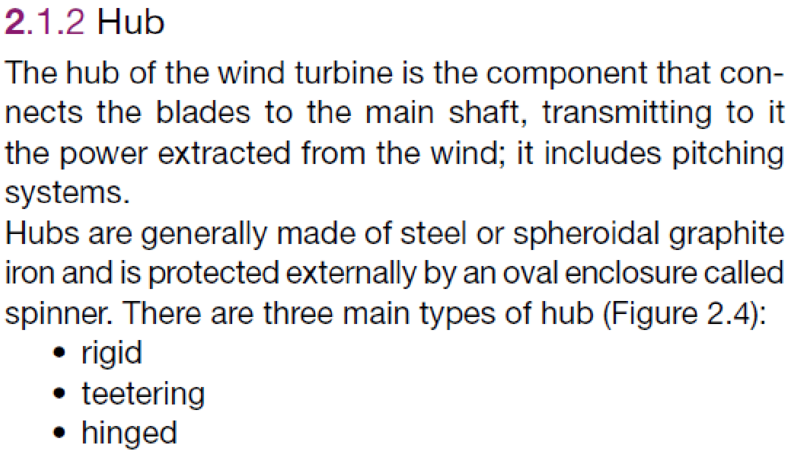
Figure 2.3

Blades

Blades bending close to tower

Image: Vestas

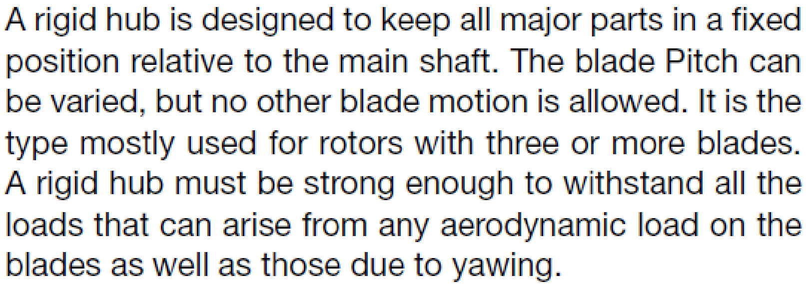
Hub



2.1.2 Hub

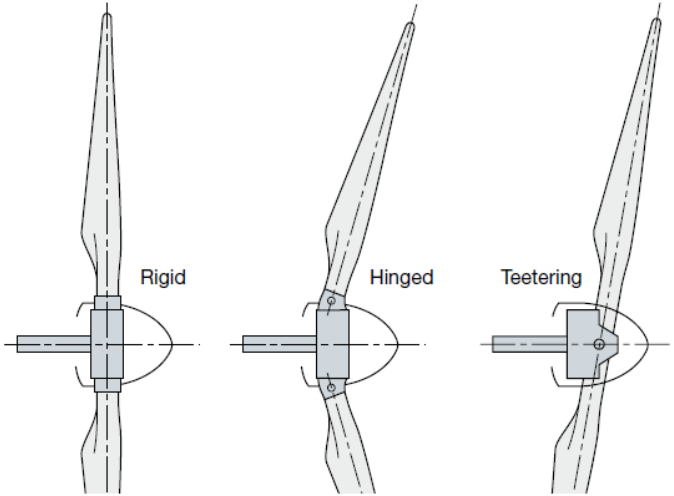
The hub of the wind turbine is the component that connects the blades to the main shaft, transmitting to it the power extracted from the wind; it includes pitching systems.
Hubs are generally made of steel or spheroidal graphite iron and is protected externally by an oval enclosure called spinner. There are three main types of hub (Figure 2.4):

- rigid
- teetering
- hinged



A rigid hub is designed to keep all major parts in a fixed position relative to the main shaft. The blade Pitch can be varied, but no other blade motion is allowed. It is the type mostly used for rotors with three or more blades. A rigid hub must be strong enough to withstand all the loads that can arise from any aerodynamic load on the blades as well as those due to yawing.

Figure 2.4

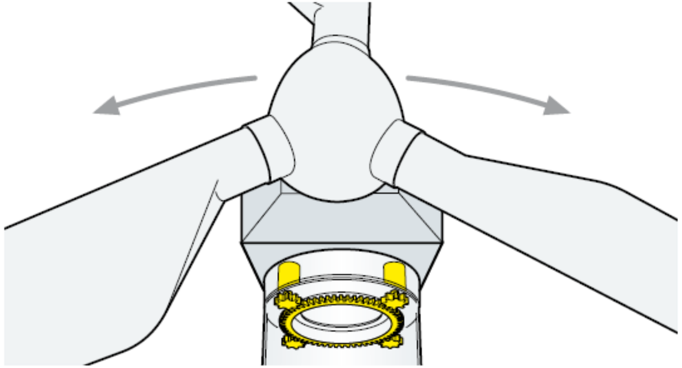


Yaw system

2.6 Yaw system

The nacelle is made to rotate on the top of the tower by an active yaw control system consisting of electrical actuators and relevant reduction gears (Figure 2.7), so that the rotor is always transversal to wind.
The direction and speed of the wind are continuously controlled by the sensors connected on the roof of the nacelle.
The rotor is generally positioned according to the average direction of the wind, calculated over a 10min period by the turbine control system.

Figure 2.7



Tower

In onshore plants the nacelle is usually at a height equal to 1 or 1.2 times the rotor diameter, whereas in offshore plants the height is equal to 0.8 times the rotor diameter.

Tubular towers are usually made of rolled steel, although sometimes reinforced concrete is used.

They are cone-shaped, with the base diameter longer than that on the top where the nacelle is positioned.

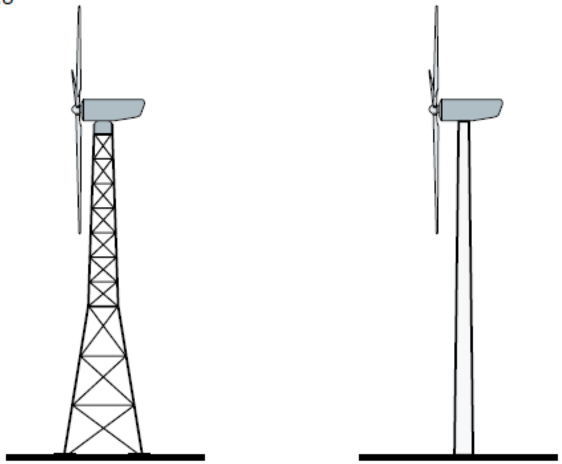
The different sections are joined and fixed together by bolted flanges.

These types of towers generate a remarkable downwind wake; that is why in most cases the rotor is positioned upwind.

Moreover, they are very visible structures and therefore they must not show signs of corrosion over many years: to this purpose, adequate coating must be chosen.

The towers are set into the ground through foundations generally consisting in reinforced concrete plinths placed at a certain depth.

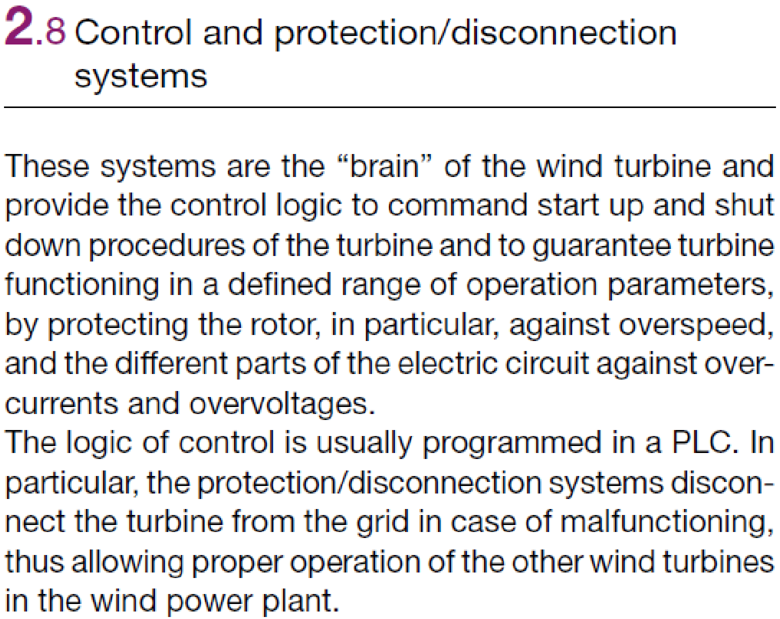
Figure 2.8



Truss tower

Tubular tower

Control and protection



2.8 Control and protection/disconnection systems

These systems are the "brain" of the wind turbine and provide the control logic to command start up and shut down procedures of the turbine and to guarantee turbine functioning in a defined range of operation parameters, by protecting the rotor, in particular, against overspeed, and the different parts of the electric circuit against overcurrents and overvoltages.

The logic of control is usually programmed in a PLC. In particular, the protection/disconnection systems disconnect the turbine from the grid in case of malfunctioning, thus allowing proper operation of the other wind turbines in the wind power plant.

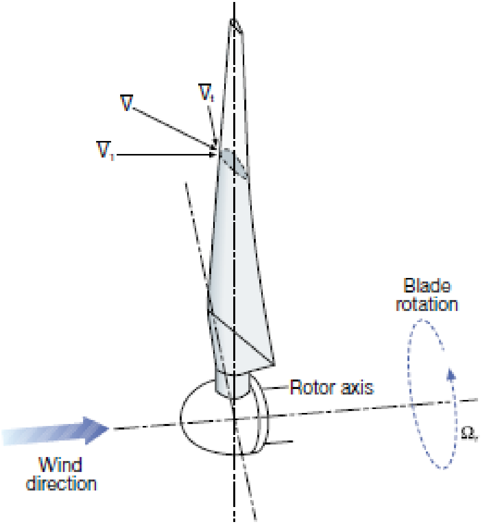
Aerodynamics analysis of blades

3.3 Aerodynamics analysis of blades

A blade is essentially a wing on which two air flows act depending on (Figure 3.9):

1. wind entering the stream tube with absolute velocity $\bar{V}_1$ parallel to the turbine axis;
2. rotation of the blade creating a drag velocity component $\bar{V}_t$ perpendicular to the above mentioned velocity vector.

Figure 3.9

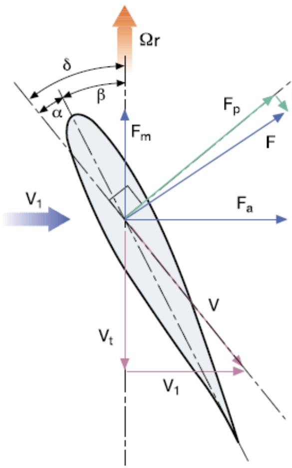


3.3.1 Lift and drag forces

The effect of the resulting air flow (v) over the airfoil of the blade is the creation of two aerodynamic forces defined as (Figure 3.10):

- *lift force*[7] F_p perpendicular to the direction of the resulting air flow
- *drag force*[8] F_r parallel to the direction of the resulting air flow

Figure 3.10



where:

α is the *angle of attack or of incidence,* which is the angular deviation between the direction of the resulting air flow and the maximum chord of the cross-section of the blade

β is the*Pitch angle,* which is the angular deviation between the rotation plane of the blade axis and the maximum chord of the cross-section of the same

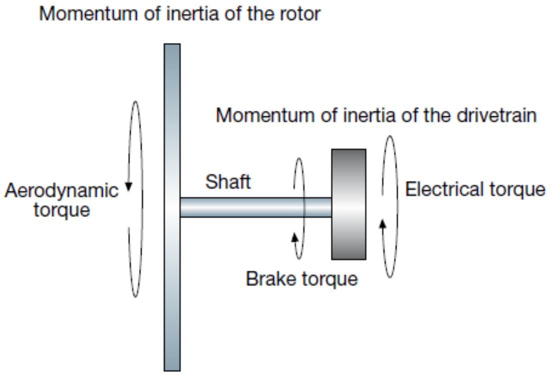
$\delta = \alpha + \beta$ is the *fabrication angle*.

Control strategies

To this mechanical model, the aerodynamic torques acting on the rotor apply: the electromagnetic torque acting on the generator and the possible torque applied to the shaft by mechanical brakes.

Below the rated wind speed, the control systems act to maximize the aerodynamic torque (and therefore the power output), whereas above the rated wind speed, the control systems modulate such torque to keep the rotation speed within acceptable limits.

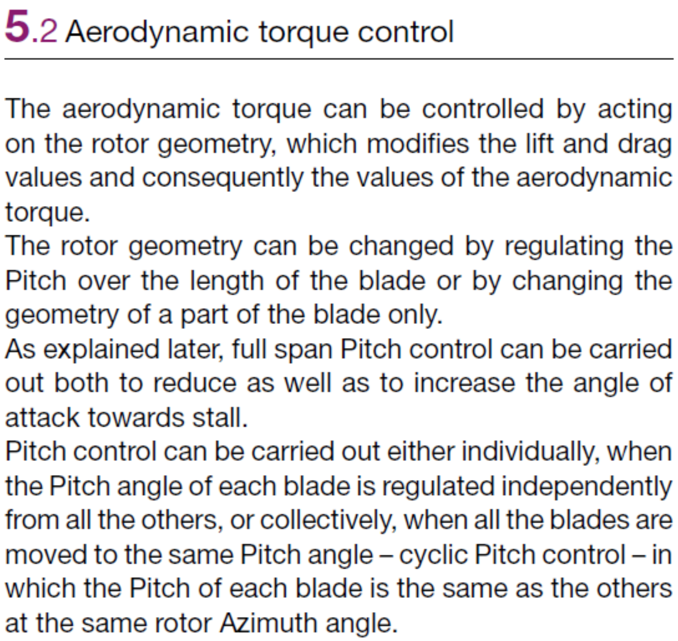
Figure 5.1



In the turbines designed to operate at nearly constant speed, the generator torque is a function of the aerodynamic torque and the only way to control the generator torque (and consequently the power output) is by regulating the aerodynamic torque.

In variable-speed turbines instead, the generator torque and the aerodynamic torque can be independently changed, and consequently the rotor speed can be controlled both acting on the aerodynamic torque as well as on the generator torque thus affecting the acceleration or deceleration of the rotor.

Control strategies



5.2 Aerodynamic torque control

The aerodynamic torque can be controlled by acting on the rotor geometry, which modifies the lift and drag values and consequently the values of the aerodynamic torque.
The rotor geometry can be changed by regulating the Pitch over the length of the blade or by changing the geometry of a part of the blade only.
As explained later, full span Pitch control can be carried out both to reduce as well as to increase the angle of attack towards stall.
Pitch control can be carried out either individually, when the Pitch angle of each blade is regulated independently from all the others, or collectively, when all the blades are moved to the same Pitch angle – cyclic Pitch control – in which the Pitch of each blade is the same as the others at the same rotor Azimuth angle.

Control strategies

5.3 Control strategies

In general, the goals of wind turbine control strategies are:

- maximizing energy production while keeping operation within the speed and load constraints of the turbine components;
- preventing extreme loads, including excessive transient and resonance loads, and minimizing fatigue stresses;
- providing acceptable quality of the power put into the grid;
- ensuring safe turbine operation.

Such goals are influenced by the operating regime of the turbine: in fact, for wind speeds lower than the rated one, the main purpose is maximizing energy production by operating at the point of maximum efficiency of the blade, whereas for higher speeds the goal is limiting the produced power by keeping it close to the rated value.

Figure 5.4