Democratic and Popular Algerian Republic Minister of Higher Education and Scientific Research "Salhi Ahmed" University Center in Nâama

Institute of Technology
Department of Electrical Engineering

Wind Energy Conversion Systems

Lessons, exercises, and solved problems.

Material specifically designed for:

- Doctoral students in Electrical Engineering (renewable energy)
- Master's in Electrical Engineering (renewable energy)
- Other disciplines related to numerical modeling of structures.

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General Introduction

General introduction

"Wind Energy Conversion Systems" is a course material authored by Medjadji Nassira from the Institute of Technology, Department of Electrical Engineering. It is designed for doctoral and master's students in Electrical Engineering with a focus on renewable energy, as well as other disciplines related to numerical modeling of structures. The material covers wind characteristics, wind power production, Weibull distribution, wind profile calculation, wind energy conversion systems, components of wind turbines, turbine modeling, and simulations of turbine behavior.

Chapter 1: Wind Characteristics This chapter discusses wind as the horizontal movement of air, its measurement in terms of direction and speed, wind power production, and the Weibull distribution for modeling wind speed frequency histograms.

Chapter 2: Wind Energy Conversion Systems (WECS) This chapter covers wind energy, wind turbines, various components of a wind turbine (rotor, nacelle, gearbox, generator, etc.), different types of wind turbines (horizontal axis and vertical axis), blade design, and the advantages and disadvantages of wind energy.

Chapter 3: Conversion of Wind Energy The chapter delves into the conversion of wind kinetic energy into mechanical energy, Betz's law, the specific speed or tip-speed ratio, power coefficient, torque coefficient, characteristic curves of wind turbines, and mechanical energy production.

Chapter 4: Conversion of Wind Energy (Continued) This section continues the discussion on components of a wind turbine and their modeling. It introduces models for the gearbox, mechanical shaft, and turbine, including assumptions and simplifications for the simulation. The chapter also presents a Simulink diagram and results of the simulation.

The course material aims to provide a comprehensive understanding of wind energy conversion systems, including their components, operation, and mathematical modeling for analysis and simulation.

Chapter : Problems and solutions

Chapter 1:

Wind Characteristic

1- Definition, Measurement, and Units of Measurement

In meteorology, wind refers to the horizontal movement of air. Its measurement comprises two parameters: its direction and its speed or force. Speed is commonly expressed in km/h or m/s. Mariners and pilots use knots (1 knot = 1.852 km/h). Wind measurement is always an average over a given period. An anemometer is used to measure wind speed. A wind vane measures wind direction by orienting itself in the direction of the wind. Three categories are distinguished: instantaneous wind, mean wind, and gusts. Instantaneous wind is measured over a 3-second period. Mean wind is calculated over a 10-minute period. A gust is a sudden increase in instantaneous wind, exceeding the mean wind by more than 10 knots (18 km/h).

2- Wind Power Production

Wind energy resources result from the movement of air masses, indirectly caused by the heating of certain areas of the Earth and the cooling of others, creating a pressure difference that keeps air masses in perpetual motion.

2.1- Weibull Distribution

As it is challenging to handle all the data related to a wind frequency distribution, it is more suitable for theoretical considerations to model the wind speed frequency histogram with a continuous mathematical function rather than a discrete value table. One can opt for the Weibull model. Indeed, for periods ranging from a few weeks to a year, the Weibull function reasonably represents the observed speeds. It is a probability density function expressed as follows: $P(V) = \left(\frac{K}{C}\right)\left(\frac{V}{C}\right)^{k-1} exp\left(-\left(\frac{V}{C}\right)^{k}\right)$

Where: P(v) is the probability density of speed V: $V_{moy} = \int V \times P(V) \times dV$

2.2 Determination of Weibull Parameters

There are several methods to determine K and C from a given wind distribution:

$B = 1 - 0.81\left(V_{moy} - 1\right)^{0.089}$; $C = \frac{1.125 \times V_{moy}}{1-B}$ (Where C is the scale factor of the Weibull curve expressed in m/s; it allows the characterization of a characteristic speed's chronology and is proportional to the average wind speed. The average wind speed can be found by integrating the probability density function, as given by the formula:

Thus, the Weibull distribution can greatly facilitate many calculations required for wind data analysis.)

$K = 1 + 0.483\left(V_{moy} - 1\right)^{0.51}$ (The shape factor of the curve (dimensionless), it determines the shape of the distribution and accepts a value from 1 to 3. A lower value would imply highly variable wind, while a constant wind would imply a higher K value)

Example 1: (The solution is in Appendix 1)

Complete filling in the table below and find the formula for the equation P(V).

Class (m/s)		Frequency %	Class x Freq
0	1	2.75	
1	2	7.8	
2	3	11.64	
3	4	13.79	
4	5	14.2	
5	6	13.15	
6	7	11.14	
7	8	8.7	
8	9	6.34	
9	10	4.3	
10	11	2.73	
11	12	1.62	
12	13	0.91	
13	14	0.48	
14	15	0.24	
15	16	0.11	
16	17	0.05	
17	18	0.02	
18	19	0.01	
19	20	0	
Sum		99.98	

Average Speed	

So, The probability density function of velocity:

$$P(V) = \left(\frac{V}{\dots\dots\dots}\right)^{\dots\dots\dots} exp\left(-\left(\frac{V}{\dots\dots\dots}\right)^{\dots\dots\dots}\right)$$

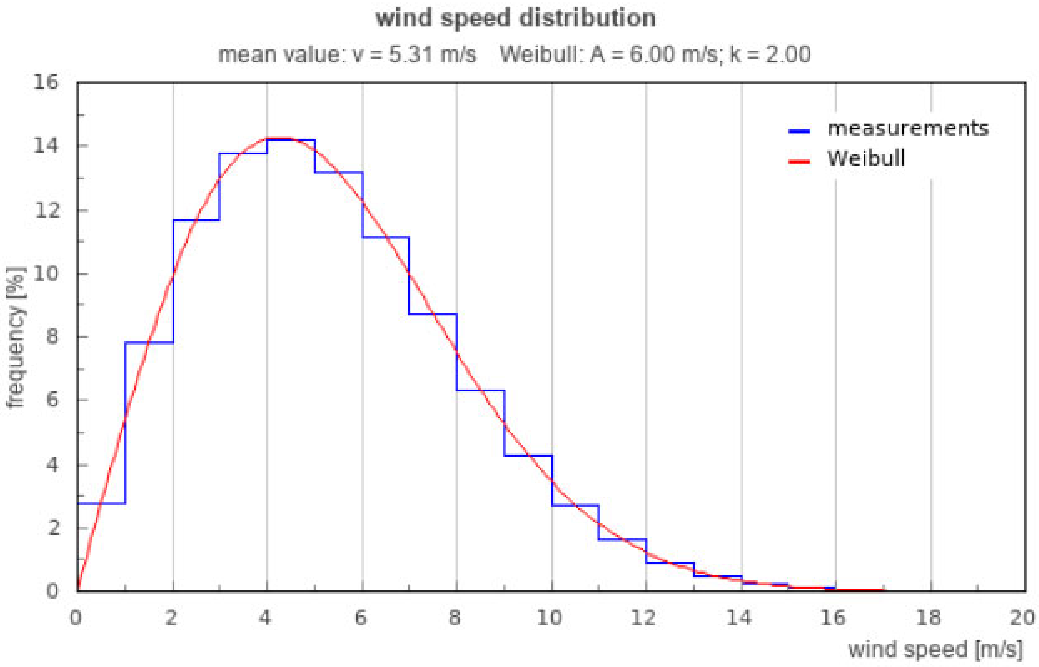


Fig 1-1. Wind speed distribution

3. Wind Profile Calculation

At ground level, the wind is strongly influenced by obstacles and terrain features. At a certain height, within the geostrophic layers (at approximately 5 km altitude), the wind is no longer affected by the surface. Between these two points, wind speed varies with altitude. This phenomenon is known as vertical wind shear. Over flat terrain and under neutral atmospheric stratification, the logarithmic wind profile provides a good approximation of vertical shear: $V_2 = V_1 \frac{ln\left(\frac{H_2}{Z_0}\right)}{ln\left(\frac{H_1}{Z_0}\right)}$

The reference velocity V_1 is measured at the reference height H_1, and V_2 is the wind speed at height H_2.

Z_0 is the roughness length (see table below). (Appendix 1)

3.1. Wind Profile Calculation

Roughness Class	**Roughness Length (z0)**	**Types of surfaces**
0	0.0002m	
0.5	0.0024m	
1	0.03m	
1.5	0.055m	
2	0.1m	
2.5	0.2m	
3	0.4m	
3.5	0.6m	
4	1.6m	

Example 2: (The solution is in Appendix 2)

Complete filling in the table below and finish drawing the graph:

Z0	0.01	Roughness length	
H1	10m	V1	5m/s
h		v	
10		5	
20			
30			
40			
50			
60			
70			
80			
90			
100			
110			
120			
130			
140			
150			

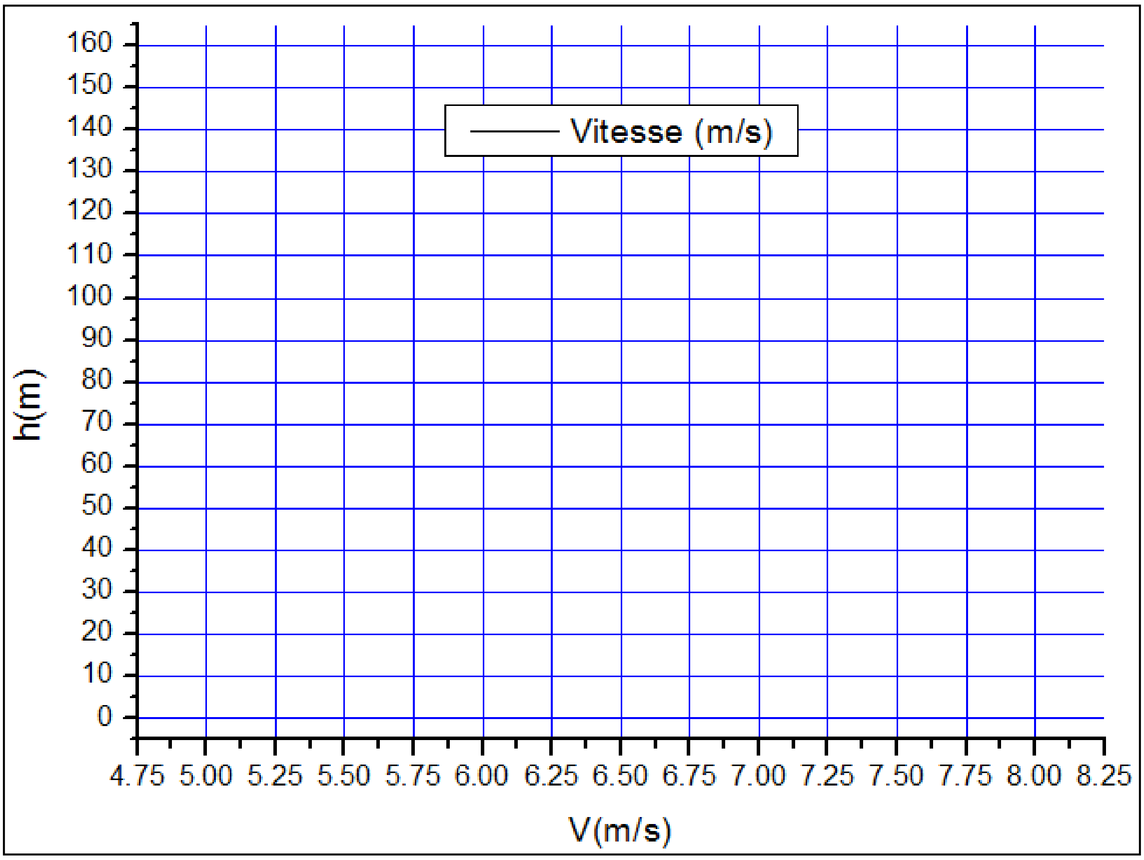


Fig 1-2. Variation of wind speed with respect to height H

Exercises of chapter 1

Exercise 1:

If the actual wind speed (at a height of H = 150m) is 12 m/s, find the wind speed at ground level (H = 10m) for the different roughness classes:

- Class (0): Water: seas, lakes
- Class (2): Agricultural land with some buildings and hedges of 8 m height, spaced about 500 m apart
- Class (4): Large cities with tall buildings and skyscrapers

Exercise 2:

Find the actual wind speed (at a height of H = 150m) if the wind speed at ground level (H = 10m) is 6 m/s for the different roughness classes:

- Class (0): Water: seas, lakes
- Class (2): Agricultural land with some buildings and hedges of 8 m height, spaced about 500 m apart
- Class (4): Large cities with tall buildings and skyscrapers

Exercise 3:

Find the probability density function of the wind speed: P(V) for the following table:

Class (m/s)	**Frequency %**	**Class x Freq**
0-1	1.94384449	
1-2	2.37580994	
2-3	2.80777538	
3-4	3.0237581	
4-5	4.31965443	
5-6	7.91936645	
6-7	8.63930886	
7-8	10.0791937	
8-9	9.35925126	
9-10	8.63930886	
10-11	7.19942405	
11-12	6.91144708	
12-13	6.33549316	
13-14	5.39956803	
14-15	4.67962563	
15-16	3.23974082	
16-17	2.30381569	
17-18	1.87185025	
18-19	1.58387329	
19-20	1.36789057	
Σ		
	Average speed	

Vitesse moyenne=

$B =$

$C =$

$K =$

$K/C =$

Plot (in Figure 1) the three wind speed profiles for the three roughness classes (0, 3, 4) if the wind speed V1 = 5 m/s at height H1 = 10 m.

Z0	**0.0002**		Z0	0.4		**Z0**	**1.6**
h	**v**		h	v		**h**	**v**
10	**5**		10	5		**10**	**5**
20			20			20	
30			30			30	
40			40			40	
50			50			50	
60			60			60	
70			70			70	
80			80			80	

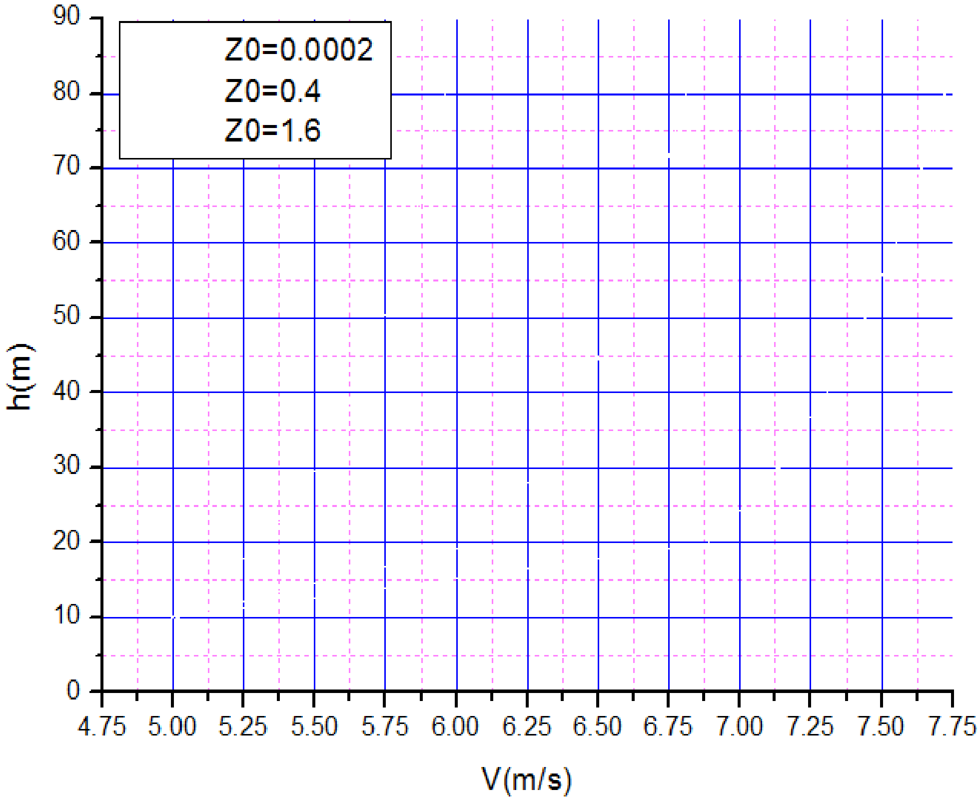


Fig 1-3. Variation of wind speed with respect to height H

Exercises (Solutions)

Exercise 1:

If the actual wind speed (at a height of H=150m) is 12 m/s, the wind speed at the ground level (H=10m) is:

Class (0): : $V_2 = ln\left(\frac{H_2}{Z_0}\right)/ln\left(\frac{H_1}{Z_0}\right) \Rightarrow V_1 = V_2 \times ln\left(\frac{H_1}{Z_0}\right)/ln\left(\frac{H_2}{Z_0}\right)$ Therefore,

$\boldsymbol{V_1 = 9.6m/s}$

Class (2): Therefore,

V1=7.556 m/s

Class (4): Therefore,

V1=4.84 m/s

Exercise 2:

The actual wind speed (at a height of H=150m) if the wind speed at the ground level (H=10m) is 6 m/s is:

- **Class (0):** : $V_2 = ln\left(\frac{H_2}{Z_0}\right)/ln\left(\frac{H_1}{Z_0}\right)$ Therefore, V2=7.50 m/s.
- **Class (2):** Therefore,
  V1=9.53 m/s.
- **Class (4):** Therefore,
  V1=14.87 m/s.

Exercise 3:

Find the probability density function of the wind speed P(V) for the following table:

$$P(V) = \left(\frac{K}{C}\right)\left(\frac{V}{C}\right)^{k-1} exp\left(-\left(\frac{V}{C}\right)^{k}\right)$$

Class (m/s)	**Frequency %**	**Class x Freq**
0-1	1.94384449	0.97192225
1-2	2.37580994	3.56371491
2-3	2.80777538	7.01943845
3-4	3.0237581	10.5831534
4-5	4.31965443	19.4384449
5-6	7.91936645	43.5565155
6-7	8.63930886	56.1555076
7-8	10.0791937	75.5939528
8-9	9.35925126	79.5536357
9-10	8.63930886	82.0734342
10-11	7.19942405	75.5939525
11-12	6.91144708	79.4816414
12-13	6.33549316	79.1936645
13-14	5.39956803	72.8941684
14-15	4.67962563	67.8545716
15-16	3.23974082	50.2159827
16-17	2.30381569	38.0129589
17-18	1.87185025	32.7573794
18-19	1.58387329	29.3016559
19-20	1.36789057	26.6738661
Σ	100	930.489561
	Average speed	**9.30 m/s**

$B = 0.022$

$C = 10.70$

$K = 2.332$

$K/C = 0.218$

$$P(V) = 0.218 \left(\frac{V}{10.7}\right)^{1.33} exp\left(-\left(\frac{V}{10.7}\right)^{2.33}\right)$$

Plot (in Figure 1) the three wind speed profiles for the three roughness classes (0, 3, 4) if the wind speed V1 = 5 m/s at height H1 = 10 m.

Z0	**0.0002**		Z0	0.4		**Z0**	**1.6**
h	**v**		h	v		**h**	**v**
10	**5**		10	5		**10**	**5**
20	6.38437785		20	6.0766914		20	6.89117699
30	6.60922447		30	6.29070184		30	7.1338722
40	6.76875569		40	6.44254467		40	7.30606719
50	6.89249772		50	6.56032312		50	7.439632
60	6.99360232		60	6.65655512		60	7.5487624
70	7.07908504		70	6.73791812		70	7.64103083
80	7.15313354		80	6.80839795		80	7.72095739

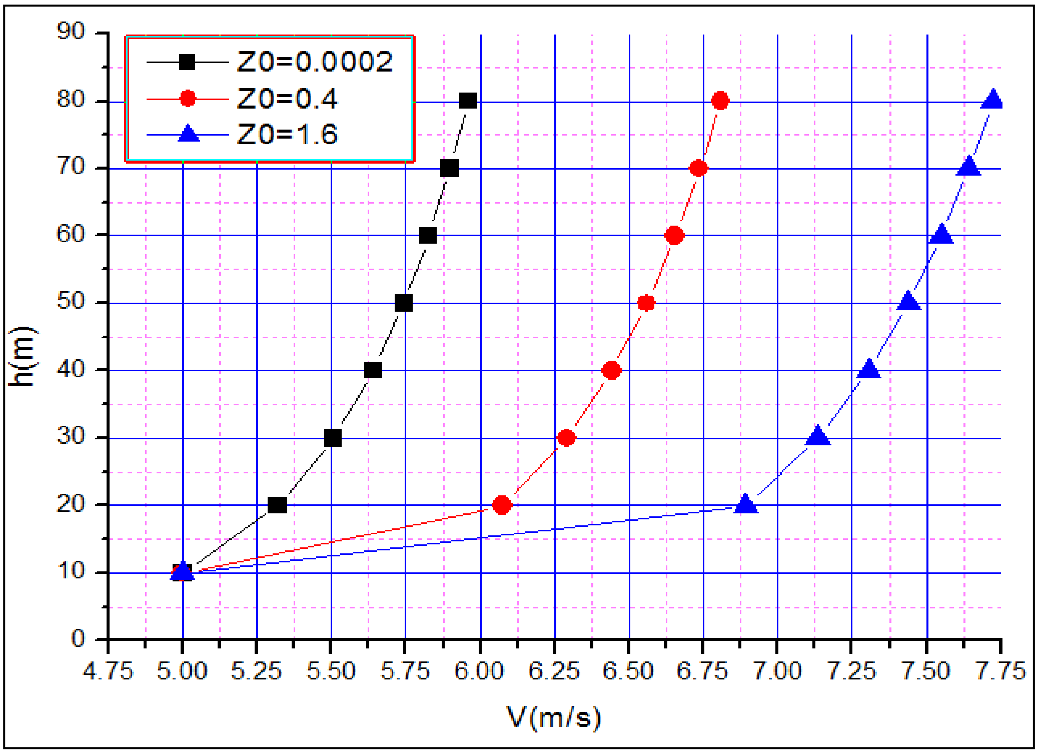


Fig 1-. Variation of wind speed with respect to height H (Solution)

Chapter 2 : Wind Energy Conversion Systems (WECS)

1- Definitions

1-1. Wind Energy

Energy from the wind flows through the wind turbine, which serves as an interface between the field of fluid mechanics and traditional mechanics. The wind turbine captures the kinetic energy present in the wind and converts it into mechanical rotational energy. This mechanical energy can be primarily utilized in two ways:

Directly to drive, for example, a water lifting pump.

To drive an electrical generator.

In the case of electrical energy production, two types of configurations can be distinguished:

Energy is stored in accumulators for later use.

Energy is used directly by injection into a distribution network. In the second configuration, the wind generator can operate either independently or in parallel with another source of electrical energy. Isolated generators are usually of relatively low power (up to 20 kW). For operation in parallel with other sources of electrical energy, the powers are much higher (100 kW and more); the minimal cost of the produced kilowatt-hour is the objective that will determine the sizing, choice, and arrangement of the various components.

Depending on the power range produced by the wind turbine, the following categories of wind turbines are distinguished:

Small-scale wind turbines: covering the power range from 20W to 50kW, divided into three categories: micro wind turbines, up to 100W maximum; mini wind turbines, from 100W to 10kW; and small wind turbines, from 10 to 50 kW.

Medium-scale wind turbines: from 50kW to several hundred kW.

Large-scale wind turbines: greater than 1 MW.

1-2. Wind Turbine

A wind turbine is a device that converts a portion of the kinetic energy of the wind (moving fluid) into mechanical energy available on a transmission shaft and then into electrical energy through a generator.

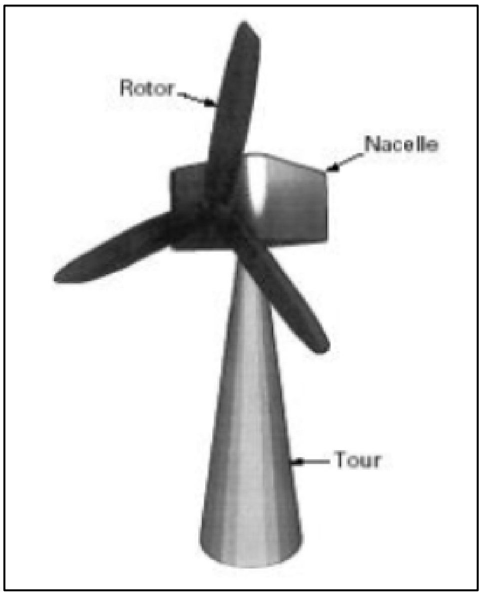


Fig 2-1 : Components of a wind turbine.

1-3. Rotor:

The rotor is the energy capture component that transforms the wind's energy into mechanical energy. The rotor is an assembly composed of blades and the primary shaft, with the hub ensuring the connection between these elements.

1-4. Nacelle:

Its role is to house the electrical energy generation installation and its peripherals. Different configurations can be encountered depending on the type of the machine. Figure 2-1 shows a section of a nacelle with its various components:

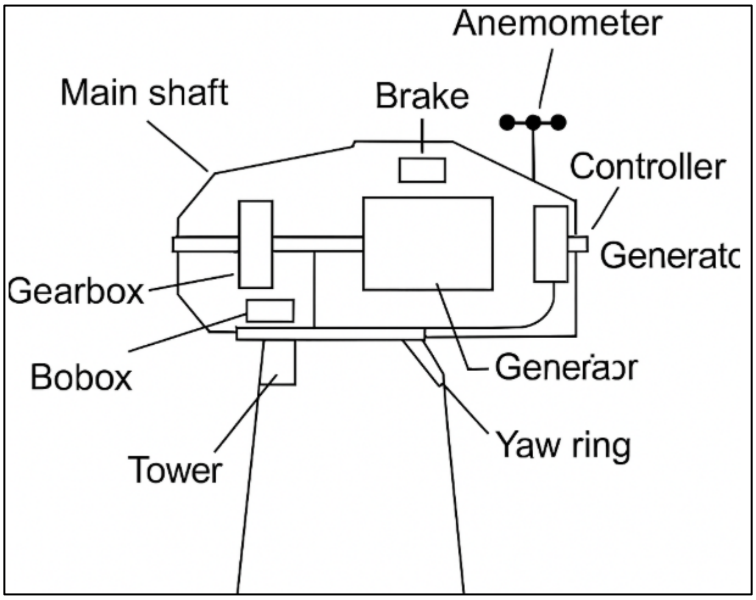


Fig 2-2: Nacelle Components

1-5. Gearbox:

It is used to increase the rotational speed between the primary shaft and the secondary shaft that drives the electrical generator. Indeed, the low rotational speed of the wind turbine would not allow for efficient electricity generation with standard current generators.

1-2-1. Secondary shaft:

It typically includes a mechanical brake to immobilize the rotor during maintenance operations and to prevent the machine from over speeding.

1-2-2. Generator:

Various types of generators can be encountered.

1-2-3. Electronic controller:

Responsible for monitoring the wind turbine's operation, the electronic controller functions as a computer that can manage the machine's start-up when the wind speed is sufficient (around 5 m/s), control the blade pitch, brake the machine, and orient the rotor and nacelle assembly into the wind to maximize energy recovery and reduce transient loads on the installation. To perform these various tasks, the controller uses data provided by an anemometer (wind speed) and a wind vane (wind direction), usually located at the back of the nacelle. Finally, the controller also manages various potential faults that may occur.

1-2-4. Cooling devices:

These include fans, water radiators, or oil radiators to cool components like the generator and gearbox.

1-2-5. Nacelle orientation device:

This device allows the rotation of the nacelle at the upper end of the tower around the vertical axis. The orientation is usually achieved using electric motors through a toothed ring. Many wind turbines have a mechanical locking system to hold the nacelle in a specific orientation. This prevents the constant use of the motors and allows for the locking of the wind turbine during maintenance operations.

1-2-6. Tower:

The tower serves two main purposes: to support the rotor and nacelle to prevent the blades from touching the ground and to position the rotor at a sufficient height to get it out of the wind gradient near the ground, thus improving energy capture. Some manufacturers offer various tower heights for the same assembly (rotor, nacelle) to better adapt to different installation sites.

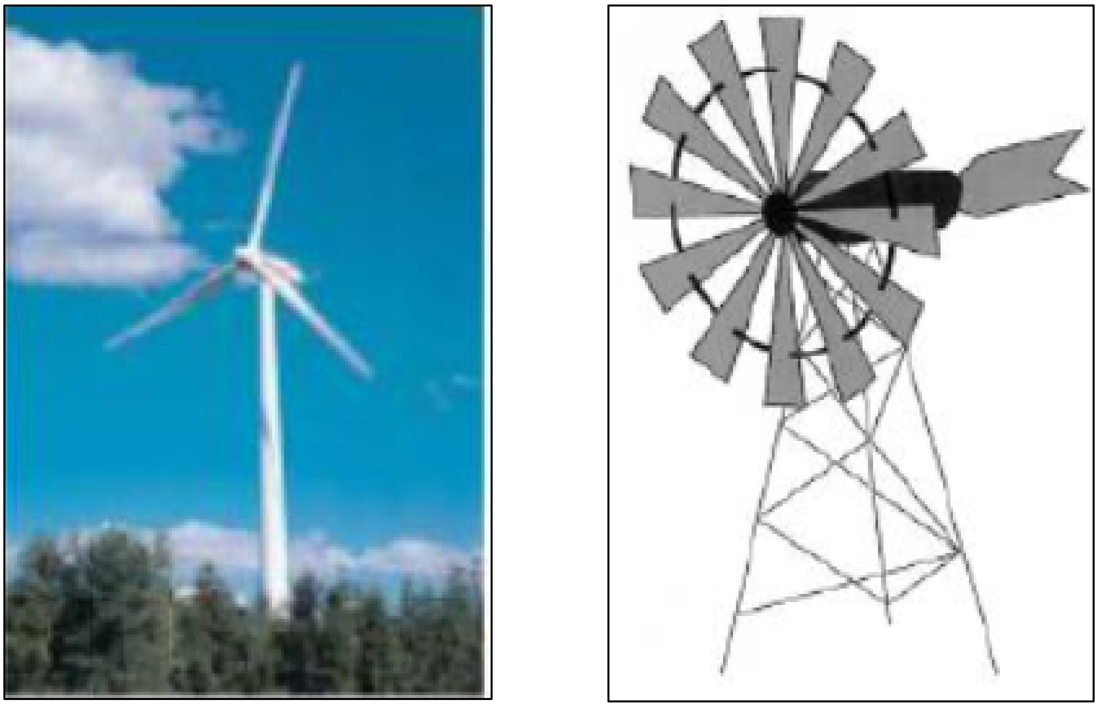
1-6. Different Types of Wind Turbines:

Wind turbines are classified based on the geometric arrangement of the shaft on which the propeller is mounted. There are primarily two types of wind turbines:

- ☐ Horizontal Axis Wind Turbines (HAWT).
- ☐ Vertical Axis Wind Turbines (VAWT).

1-3-1. Horizontal Axis Wind Turbines (HAWT):

Most of the currently installed wind turbines use horizontal axis turbines. Various wind turbine constructions use two, three blades (the most common), or multi-blades (Figure 2-3).



(a) *(b)*

Fig 2-3: Three-Blade and Multi-Blade Wind Turbines

(a) Horizontal Three-Blade Wind Turbine
(b) Horizontal Multi-Blade Wind Turbine

The rotor can be positioned in front of the nacelle (upstream wind turbine), in which case a mechanical system for orienting the active surface of the wind turbine "into the wind" is necessary. Another solution that lightens the construction by eliminating any mechanical orientation device is to place the turbine behind the nacelle (downstream wind turbine). In this case, the turbine automatically positions itself into the wind. Wind turbines of this type are relatively rare because significant vibrations occur due to the blades passing behind the tower.

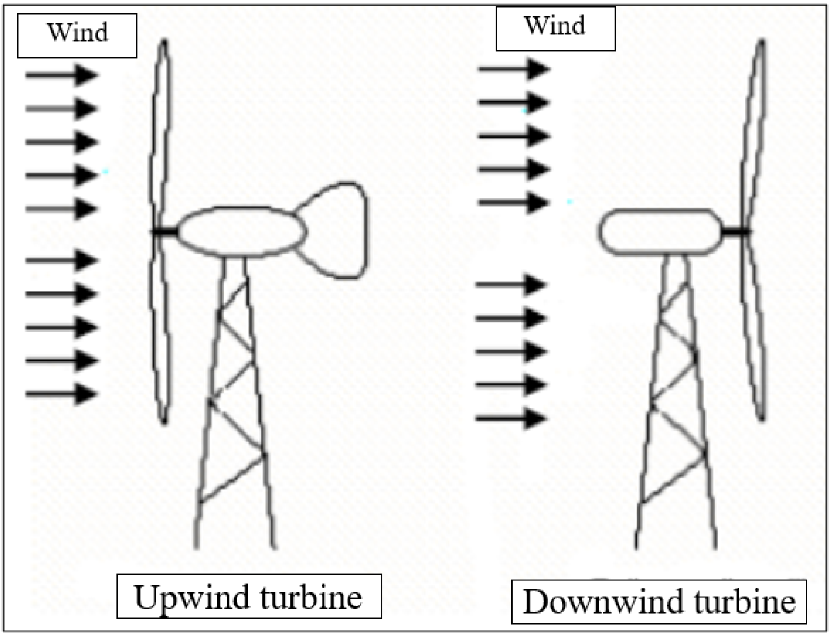


Fig 2-4: Horizontal Axis Configurations

1-3-2. Vertical Axis Wind Turbines (VAWT):

They have certain advantages: ground-based machinery, no need for wind direction orientation, and often simple construction. They rotate at low speeds and are therefore less noisy. However, they pose challenges for mechanical guidance, with the lower bearing having to support the weight of the entire turbine.

There are mainly three technologies for this type of wind turbines:

☐ Classic Darrieus turbines.
☐ Straight-bladed Darrieus turbines (type-H).
☐ Savonius turbines.

Darrieus Turbine

Darrieus Type-H

Turbine Savonius

Fig 2-5: Vertical Axis Wind Turbines

2- Blade Design:

Horizontal axis wind turbines are the most common due to their high efficiency. Today, engineers avoid building large wind turbines with an even number of blades, primarily for stability reasons. In the case of a wind turbine with a rigid structure, there would be stability issues if the rotor has an even number of blades: when the upper blade flexes slightly backward, reaching the farthest point and thus capturing the maximum wind power, the lower blade passes through the sheltered zone created just in front of the tower.

Low-speed wind turbines are equipped with a large number of blades (between 20 and 40), and their significant inertia generally limits their diameter to about 8 meters. Their power coefficients quickly reach their maximum values during speed increase but also decrease rapidly thereafter. High-speed wind turbines are much more common in electricity production and typically have between 1 and 3 blades.

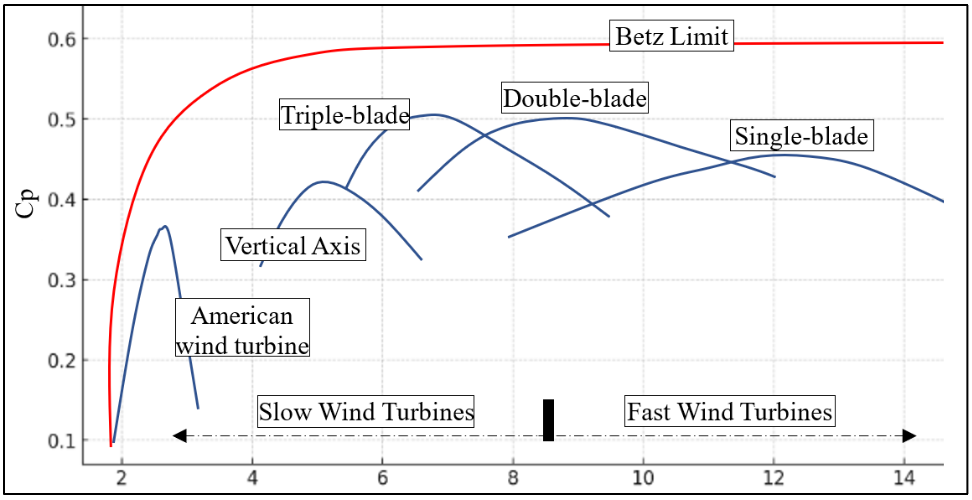


Fig 2-6: Wind Turbine Performance Curves

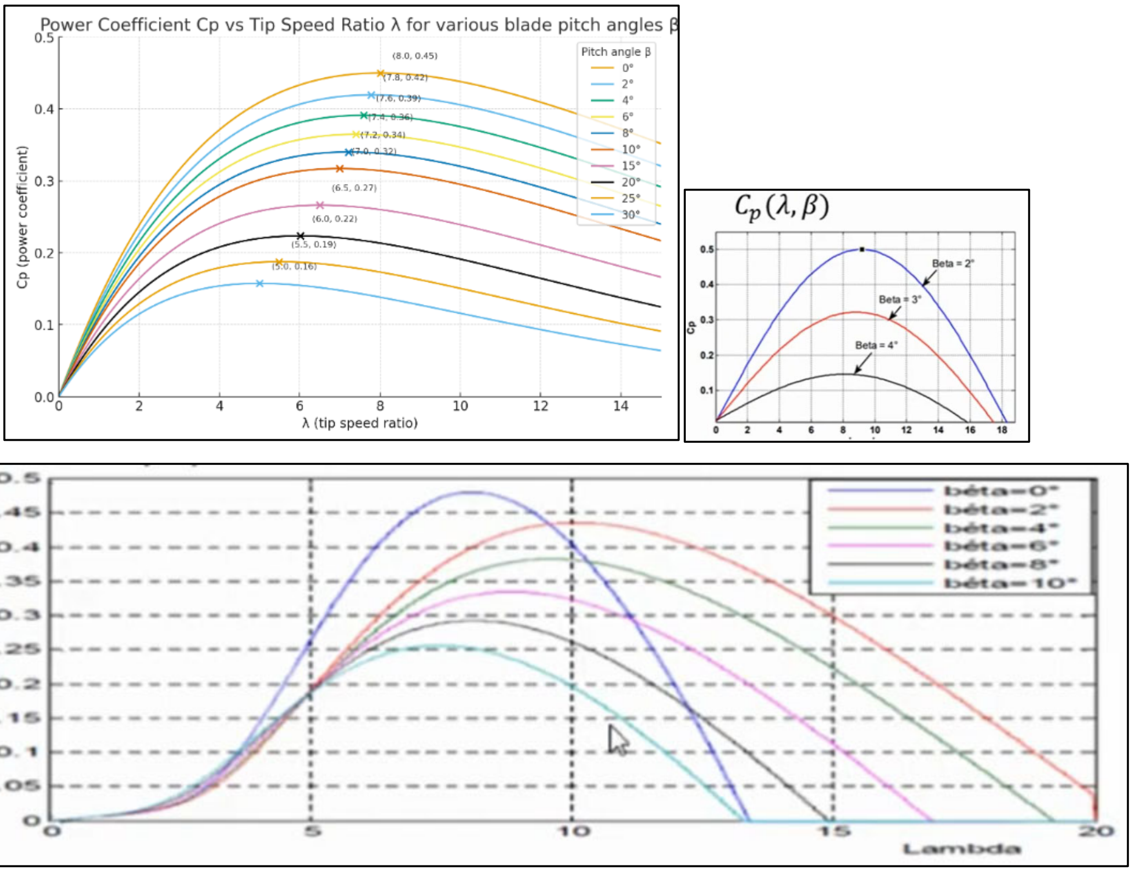


Figure 2-7: Power and Torque Coefficient Trends

2-1. Three-Blade Design:

The use of three-blade rotors predominates in medium and large-scale machines, either in operation or being built worldwide, accounting for approximately 80% of the market. This is due to their dynamic stability and visual impact. Moreover, their power coefficient reaches high values and decreases slowly as the wind speed increases.

2-2. Two-Blade Design:

Two-blade wind turbines have certain disadvantages, including the need for a much higher rotational speed to produce the same amount of energy as a three-blade wind turbine. Additionally, cyclic vibrations can occur when the nacelle tries to follow the wind, and the blades are horizontal. This requires a complex design as it must be equipped with a tilting rotor to avoid these impacts.

2-3. Single-Blade Design:

Single-blade wind turbines are relatively rare, with even more pronounced issues than two-blade wind turbines. Apart from a higher rotational speed and issues related to noise and visual impact, the drawback of this type of wind turbine is the significant torsion applied to the shaft. To balance the rotor, the wind turbine needs to be equipped with a counterweight on the side of the hub opposite to the blade.

3- Blade Materials:

Most modern blades for large wind turbines are made of plastic (polyester or epoxy) reinforced with fiberglass. Using carbon or aramid fibers as reinforcement materials is another possibility, but in general, such a solution would prove to be too expensive for large wind turbines. Composite materials like wood, wood-epoxy, or wood-fiber-epoxy have not yet penetrated the blade market, although possibilities for their use in blade manufacturing are still being explored. Steel and aluminum alloys pose issues related to weight and metal fatigue, respectively. Therefore, these alloys are currently only used for very small blades.

4- Wind Turbine Operation Strategies:

4-1. Force Balance on a Blade:

The operating modes of a wind turbine can be represented as follows: The wind speed approaching a blade element located at a radius of r is represented by the vector $\vec{V_a}$. Vector $\vec{V_1}$ represents the wind component due to the rotation of the wind turbine. The resultant of these two vectors is called the apparent wind or relative wind $\vec{W}$. This wind generates a moment M and a resultant force $\vec{R}$. This force can be decomposed into a traction force $\vec{F}_{ax}$ along the axis of the blade, directly offset by the mechanical resistance of the tower, and a force in the rotor plane $\vec{F}_{rot}$, responsible for torque.

$$C = F_{rot}.r \qquad (2\text{-}1)$$

Region (A) corresponds to that of a propeller where energy is supplied to the fluid by the blade element (airplane). When the resultant $\vec{R}$ is in region (C), it is the fluid that supplies energy to the blade. This is characteristic of aeromotor operation in wind turbines.

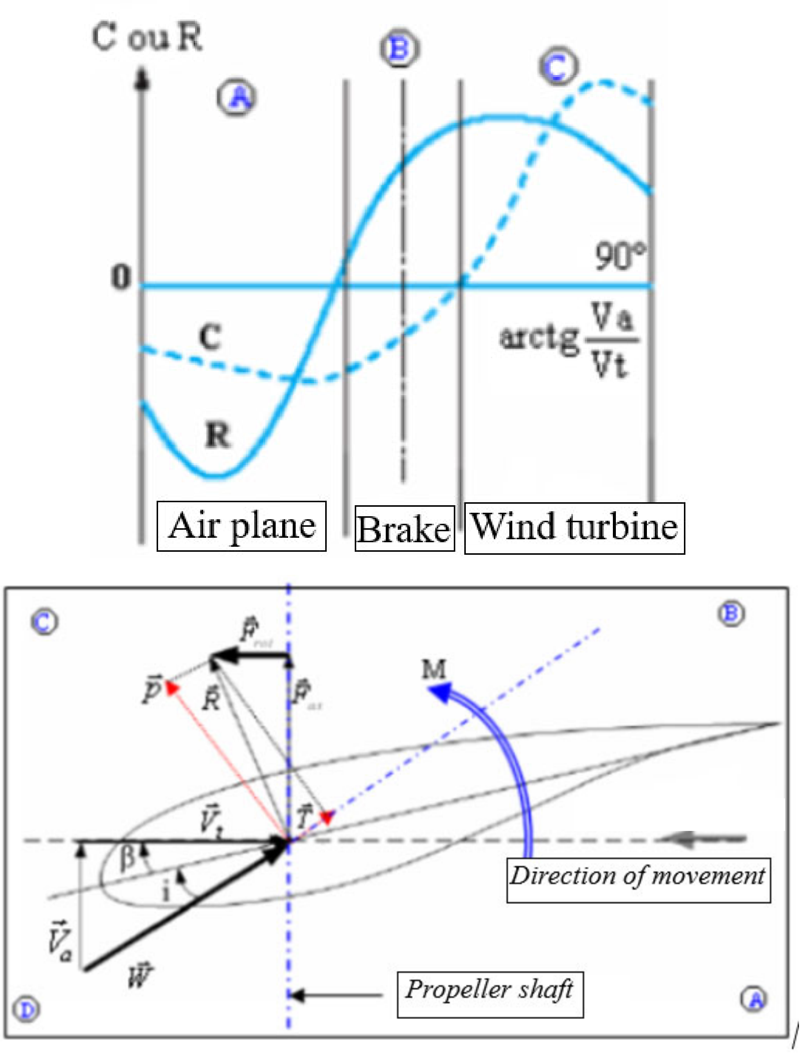


Fig 2-8: Behavior of a Blade in a Flow

The following angles are defined:

- ☐ Angle of Attack "i": the angle formed by the blade surface with the direction of the apparent wind.
- ☐ Pitch Angle "β": the angle formed by the blade and the plane of rotation.

4-2. Decomposition of the Resultant Wind Action: Thrust and Drag

The resultant R of the air actions on the blade element can be decomposed into two forces, P and T:

P (Thrust): perpendicular to the direction of the wind.

T (Drag): In the same direction as the wind.

The forces P and T can be expressed using the theorem of the variation of momentum in the form:

$$P = C_{rot}.\frac{\rho}{2}S.W^2 \qquad (2\text{-}2)$$

$$T = C_{ax}.\frac{\rho}{2}S.W^2 \qquad (2\text{-}3)$$

C_{ax} and C_{rot} are determined in a wind tunnel and provided in the form of a polar diagram as a function of the angle of attack (Figure 9).

ρ: air density.

S: area of the portion of the blade in the apparent wind.

W: apparent wind.

Knowing P and T, it is possible to express Frot and Fax in terms of the angles β and i for a given operating regime (Figure 8).

$$F_{rot} = P.Sin(\beta + i) - T.Cos(\beta + i) \qquad (2\text{-}4)$$

$$F_{ax} = P.Cos(\beta + i) + T.Sin(\beta + i) \qquad (2\text{-}5)$$

$$\beta + i = \Phi \qquad (2\text{-}6)$$

The motor torque for the considered blade portion is equal to:

$$C = r[P.Sin(\beta + i) - T.Cos(\beta + i)] \qquad (2\text{-}7)$$

The total motor torque is the sum of all elementary torques along the blade, taking into account that "i" varies from the root to the tip of the blade.

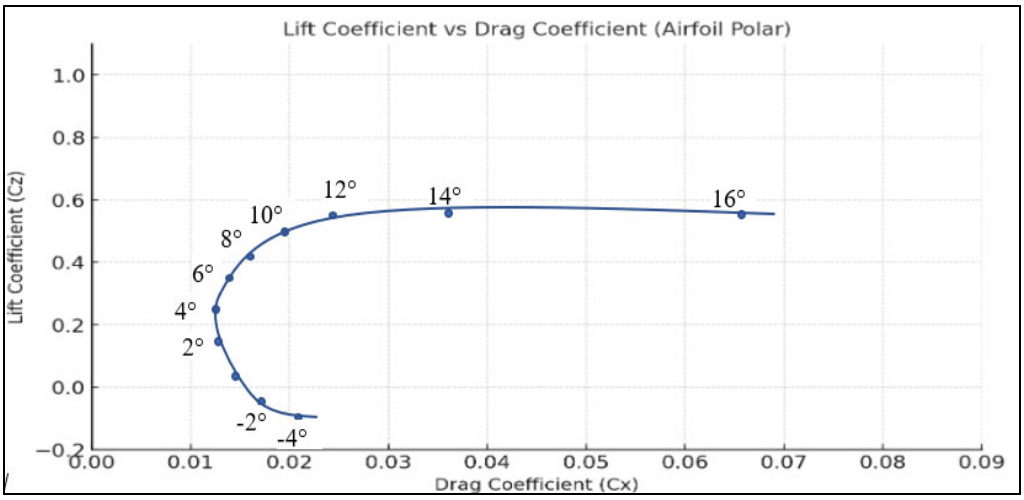


Fig 2-9: Profile Polar - i as a function of Cz and Cx

By setting $x = \frac{P}{T}$, it is demonstrated that the efficiency of the blade section, which is equal to the ratio of the power recovered to the power supplied by the wind, is a function of the ratio $\frac{C_z}{C_x}$ as a function of **i**. The graph (Figure 10) represents the variation of the **P/T** ratio, which is $\frac{C_z}{C_x}$, as a function of ***i*** .

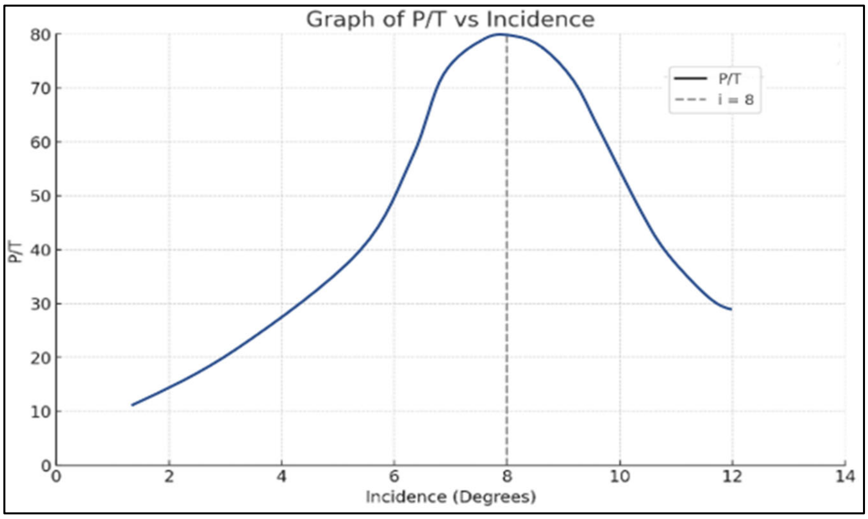


Fig 2-10: Optimum Angle of Attack for a Profile Obtained from the Polar

For each blade section, there will be an optimal angle of attack. This explains that to improve the efficiency of a propeller, it will be possible to vary the pitch of each blade section. This property will be used for regulation.

5- Advantages and Disadvantages of Wind Energy

5-1. Advantages:

Wind energy is a renewable energy source, unlike fossil fuels.

Wind energy is clean energy. It has no harmful environmental impact, unlike other energy sources that have caused radical climate change through the massive and direct production of CO2.

Wind energy poses no risks and obviously does not produce radioactive waste, unlike nuclear energy.

The operational mode of wind turbines and the ability to stop them at any time give them the advantage of having good efficiency, unlike the continuous operation mode of most thermal and nuclear power plants.

5-2. Disadvantages:

- ☐ The stochastic nature of the wind influences the quality of the produced electrical power, which poses a challenge for grid operators.
- ☐ The cost of wind energy remains higher compared to other conventional energy sources, especially in less windy locations.
- ☐ Noise, it has been significantly reduced thanks to progress in gearbox technology.

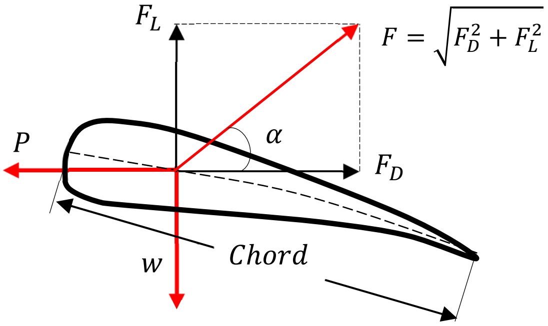
Exercises of chapter 2

Exercise 1:

A rectangular wing of a small aircraft with a length of 12 m (wingspan) and a chord length of 1.8 m is used in horizontal flight at 200 km/h. The total aerodynamic force acting on the wing is 28 kN. The ratio between lift and drag is 10, and the air density is $\rho=1.2\ kg/m^3$.

You are asked to:

1. Calculate the coefficients of lift and drag.
2. Find the total weight of the aircraft supported by this wing.
3. Determine the power required to operate the aircraft.



Exercise 2:

If the rotation speed of the propeller is N=15 RPM, and the wind speed Va=54 km/h.

- Find the tilt angles of the propeller (β) in three positions (1, 2, and 3), knowing that a1=15 m, a2=15 m, and a3=15 m. The angle of incidence is 8°.
- Find the different forces T, P, and F_{rot} in position (3).
- $F_{rot}=0.7$ $C_{rot}=0.7$, $C_{axe}=0.07$, the average surface area of the blade is 4.5 m^2, and the air density is $\rho=1.2\ kg/m^3$.
- Determine the torque in position (3).

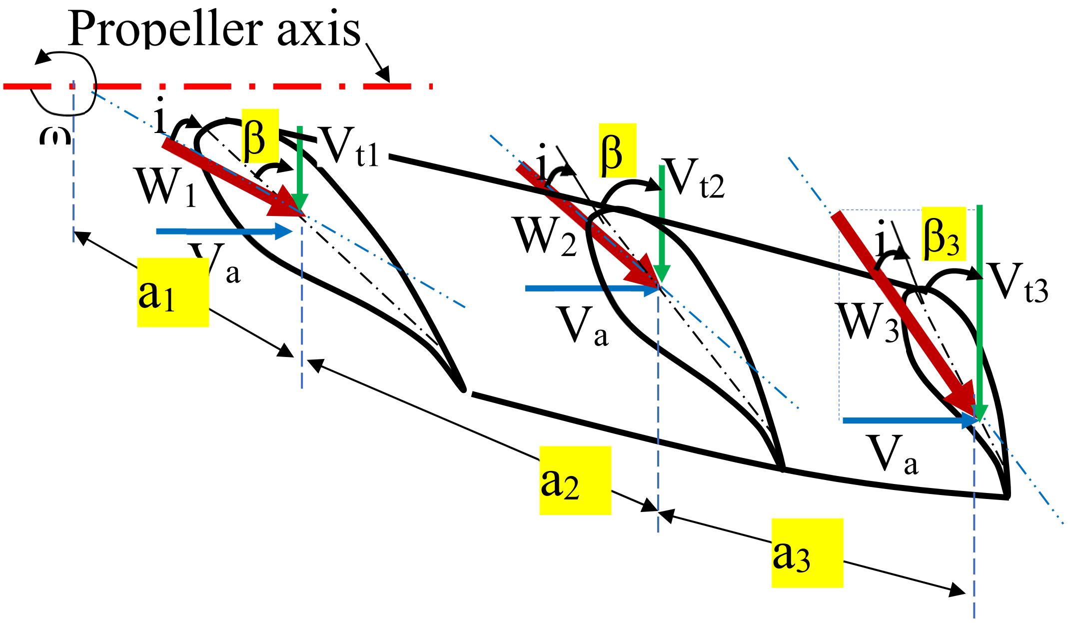
Formulas

- $V(m/s) = V(Km/h)\ \frac{1000}{3600}$

The power of the airplane engine: $P = F_D x U$

- $Vt = \omega(rd/s) \times a$
- $Vt = \frac{2\pi.N(tr/min)}{60} \times a$

- $F_D = C_D \,.\, A.\frac{\rho U^2}{2}$
- $F_L = C_L \,.\, A.\frac{\rho U^2}{2}$



Exercises (Solutions)

Exercise 1:

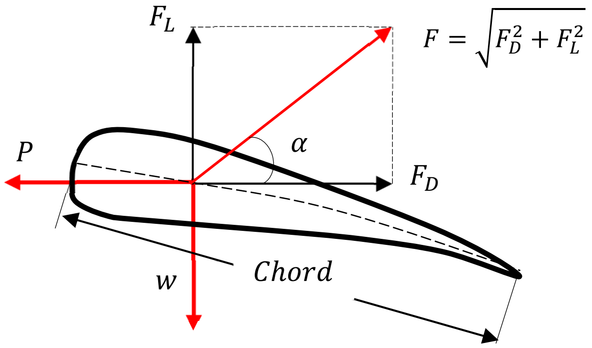
The length of the wing: 12m.

The chord of the wing: 1.8m.

The speed of the airplane: $U = \frac{200Km}{H} = \frac{200x1000}{60x60} = 55.55m/s$

The air density: ρ=1.2Kg/m^3

The total aerodynamic force: *F=28KN*



1- The lift coefficient C$_L$ and the drag coefficient **C$_D$** :

$$tg\alpha = \frac{F_L}{F_D} = 10 \Rightarrow \ \alpha = arc\ tg10 = 84.29^0$$

$$;Sin\alpha = \frac{F_L}{F} = \sin(84.29^0) = 0.995 \Rightarrow F_L = Fx0.995 = 28x0.995 = 27.86$$

$$F_L = 27.86KN$$

$$Cos\alpha = \frac{F_D}{F} = \text{Cos}(84.29^0) = 0.0995 \Rightarrow F_D = Fx0.0995 = 28x0.0995 =$$

$$;\ 2.786$$

$$F_D = 2.786KN$$

$$A = lxC = 12x1.8 = 21.6m^2$$

$$F_D = C_D\,.A.\frac{\rho U^2}{2} \Rightarrow \ C_D = \frac{2.F_D}{A.\rho U^2} = \frac{2\times2.786\times1000}{21.6\times1.2\times55.55^2}$$

$$C_D = 0.0696$$

$$F_L = C_L\,.A.\frac{\rho U^2}{2} \Rightarrow \ C_L = \frac{2.F_L}{A.\rho U^2} = \frac{2\times27.86\times1000}{21.6\times1.2\times55.55^2}$$

$$C_L = 0.696$$

$Ou\ bien \quad F_L = 10F_D$

2- The total weight of the airplane supported by this wing.

According to the figure, in horizontal flight:

$F_L = w$

3- $w = 27.86KN$

3- The power required to drive the airplane.

$$\text{P} = F_D x U = \frac{F_L}{10} x U = \frac{27.86}{10} x 55.55 = 154.76KN$$

$$\text{P} = 154.76KN$$

Exercise 2 :

1- $Va\left(\frac{m}{s}\right) = Va\left(\frac{Km}{h}\right)\frac{1000}{3600} = 54 \times \frac{1000}{3600} = 15m/s$

$$Vt1 = \frac{2\pi.N(tr/min)}{60} \times a1 = \frac{2 \times 3.14 \times 15}{60} \times 15 = 23.55m/s$$

$$Vt2 = \frac{2\pi.N(tr/min)}{60} \times a2 = \frac{2 \times 3.14 \times 15}{60} \times 30 = 47.1m/s$$

$$Vt3 = \frac{2\pi.N(tr/min)}{60} \times a3 = \frac{2 \times 3.14 \times 15}{60} \times 45 = 70.65m/s$$

$tg(i + \beta1) = \frac{Va}{Vt_1} = \frac{15}{23.55} = 0.637 \Rightarrow i + \beta1 = 32.497° \Rightarrow \beta1 = 26.50°$

$tg(i + \beta2) = \frac{Va}{Vt_2} = \frac{15}{47.1} = 0.3118 \Rightarrow i + \beta2 = 17.66° \Rightarrow \beta2 = 9.66°$

$tg(i + \beta3) = \frac{Va}{Vt_3} = \frac{15}{70.65} = 0.2123 \Rightarrow i + \beta3 = 11.98° \Rightarrow \beta3 = 3.98°$

2- $W_3 = \sqrt{Vt3^2 + Va^2} = \sqrt{70.65^2 + 15^2} \Rightarrow W_3 = 72.22m/s$

$T = C_{axe} .A.\frac{\rho {W_3}^2}{2} \Rightarrow T = 0.07 \times 4.5 \times \frac{1.2 \times 72.22^2}{2} \Rightarrow T = 985.90\text{N}$

$P = C_{rot} .A.\frac{\rho {W_3}^2}{2} \Rightarrow P = 0.7 \times 4.5 \times \frac{1.2 \times 72.22^2}{2} \Rightarrow P = 9859.04\text{N}$

$F_{rot} = P.Sin(\beta + i) - T.Cos(\beta + i) \Rightarrow$

$F_{rot} = 9859.04 \times Sin(11.98°) - 985.90 \times Cos(11.98°) \Rightarrow F_{rot} = 1082.1N$

3- $C = r \times F_{rot} = 45 \times 1082.1 \Rightarrow C = r \times F_{rot} = 45 \times 1082.1 \Rightarrow$

$C = 48960.7N.m$

Chapter 3: Conversion of Wind Energy

1- Wind Energy Conversion

1-1. Conversion of Wind Kinetic Energy into Mechanical Energy

The wind turbine is a device that converts the kinetic energy of the wind into mechanical energy. The kinetic energy of a column of air with length dx, cross-sectional area S, and density ρ, moving at a velocity v (Figure 3-1) is given by: $dE_k = 1/2\ \rho S\ dx\ v^2$ (3-1)

$$dE_C = \frac{1}{2}\rho S dx v^2 \qquad (3\text{-}1)$$

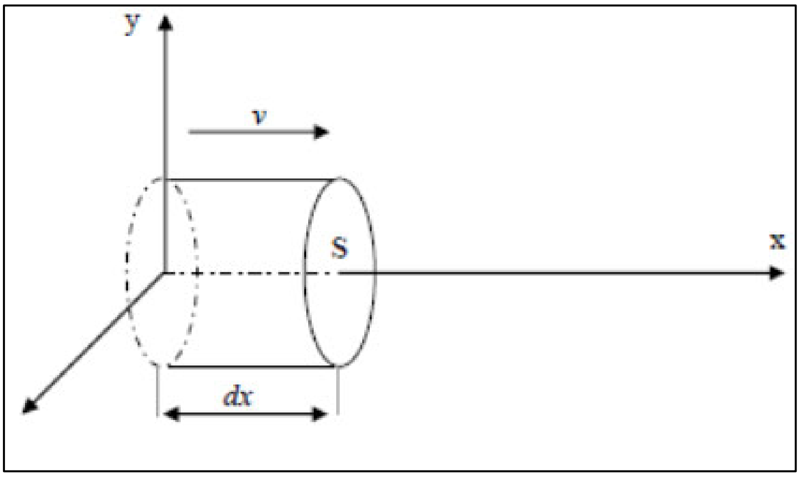


Fig 3-1: Column of air moving at velocity v

The power P_m extracted from the moving air volume is the derivative of kinetic energy with respect to time. Assuming $v = dx/dt$, we can derive the expression for P_m as follows: $P_m = (dE_k)/dt = d(1/2\ \rho S\ dx\ v^2)/dt = 1/2\ \rho S_0\ v^2\ dx/dt = 1/2\ \rho S_0\ v^2\ v$

$P_m = 1/2\ \rho S_0\ v^3$ (3-2)

Where: ρ: Air density (in kg/m³). v: Instantaneous wind velocity (in m/s). E_k: Energy in joules.

2- Betz's Law

Betz's law states that a wind turbine can never convert more than 16/27 (or 59%) of the kinetic energy contained in the wind into mechanical energy. It was the German physicist Albert Betz who first formulated Betz's law in 1929. Consider the system shown in Figure 3-2, which represents a streamtube around a horizontal-axis wind turbine. V1 represents the wind speed upstream of the wind turbine, and V2 is the velocity downstream.

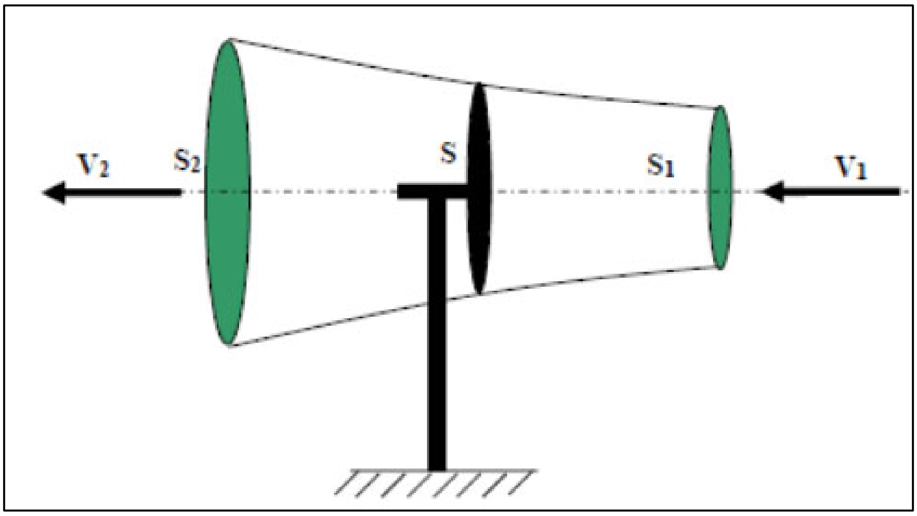


Fig 3-2: Stream tube around a wind turbine

"The mass of moving air passing through this tube in one second is given by the product of air density, surface area, and average velocity.

$$m_0 = \frac{1}{2}\rho S(v_1 + v_2) \qquad (3\text{-}3)$$

The actual power extracted by the rotor blades is the difference between the powers of the wind upstream and downstream.

$$P_m = \frac{1}{2}m_0(v_1^2 - v_2^2) \qquad (3\text{-}4)$$

By replacing m0 with its expression in (3.4), we get:

$$P_m = \frac{1}{4}\rho S(v_1 + v_2)(v_1^2 - v_2^2) \qquad (3\text{-}5)$$

The total power theoretically available on the surface S is extracted without a decrease in wind speed by setting v_2=0 in expression (3-4): $P_m = \frac{1}{2}m_0.v_1^2 = \frac{1}{2}\rho S v_1.v_1^2$ since $m_0 = \rho S v_1$.

$$P_{mt} = \frac{1}{2}\rho S v_1^3 \qquad (3\text{-}6)$$

3- The specific speed, or normalized speed, Tip-Speed-Ratio (TSR)

The tip-speed ratio, also known as the normalized speed, is defined as the ratio of the linear blade tip speed of the turbine Ωt Rt to the instantaneous wind speed v (Figure 3-3) and is given by the following expression:

$$\lambda = \frac{\Omega_t \mathrm{R}_t}{v} \qquad (3\text{-}7)$$

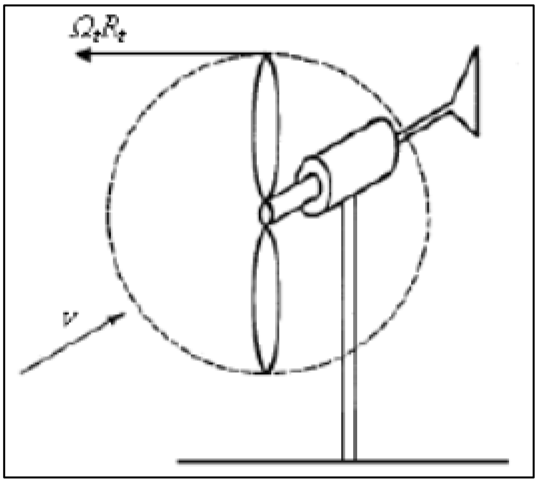


Fig 3-3: Wind speed (v) and blade tip tangential speed (Ωt Rt) Rt: Swept surface radius in meters. V: Wind speed in m/s. Ωt: Pre-gearbox rotation speed in rad/s.

4- Power Coefficient

The power coefficient, denoted Cp, is defined as the ratio of the power extracted from the wind to the total theoretically available power:

$$C_P = \frac{P_m}{P_{mt}} = \frac{\frac{1}{4}\rho S(v_1+v_2)(v_1^2-v_2^2)}{\frac{1}{2}\rho S v_1^3} = \frac{\frac{1}{2}\cdot\frac{1}{2}\rho S(v_1+v_2)(v_1^2-v_2^2)}{\frac{1}{2}\rho S v_1^3} = \frac{\frac{1}{2}(v_1+v_2)(v_1^2-v_2^2)}{v_1^3}\cdot\frac{1/v_1^3}{1/v_1^3} = \frac{\frac{(v_1+v_2)}{v_1}\cdot\frac{(v_1^2-v_2^2)}{v_1^2}}{2}$$

$$C_P = \frac{\left(1+\frac{v_2}{v_1}\right)\cdot\left(1-\left(\frac{v_2}{v_1}\right)^2\right)}{2} \qquad (3\text{-}8)$$

The Cp coefficient is variable and depends on wind speed, turbine rotation speed Ωt, and blade parameters such as angle of attack and pitch angle. It is often represented as a function of tip-speed ratio (λ). The maximum theoretical value of the power coefficient, known as **Betz's** limit, is 16/27, which is approximately 0.593.

The limit of Betz is actually never reached in reality, and the best horizontal-axis machines, whether bi-blade or tri-blade, operate at around 60-65% of the **Betz** limit; in total, only 40% of the wind energy is recovered. We can then deduce the aerodynamic efficiency:

$$\eta = \frac{16}{27} C_{Pmax} \qquad (3\text{-}9)$$

Where Cpmax is the maximum value that the power coefficient Cp can take. This value is associated with a nominal specific speed λopt for which the turbine has been sized according to a nominal wind speed Vn and a nominal rotation speed Ωtn.

5- Torque Coefficient

The torque coefficient Cm is quite close to the power coefficient Cp. It is useful for estimating the torque values at different operating points, especially at zero rotation speed Ωt, which corresponds to a Cp value of zero for a non-zero Cm value.

By combining equations (3.6), (3.7), and (3.8), the available mechanical power Pm on the turbine's shaft can be expressed as: $P_m = \frac{1}{2} C_P(\lambda)\rho S. v_1^3$

$$P_m = \frac{1}{2} C_P(\lambda)\rho\pi R^2. v_1^3 \qquad (3\text{-}10)$$

With:

$$\lambda = \frac{\Omega_t \mathrm{R}_t}{v} \qquad (3\text{-}7)$$

$$\Omega_t = \frac{\lambda. v}{\mathrm{R}_t}$$

So the expression for torque is as follows:

$$T_t = \frac{P_m}{\Omega_t} = \frac{P_m \mathrm{R}_t}{\lambda v} = \frac{\frac{1}{2} C_P(\lambda)\rho\pi R^2. v_1^3 R_t}{\lambda v} = \frac{1}{2\lambda} C_P \rho\pi R_t^3. v_1^2$$

$$T_t = \frac{P_m}{\Omega_t} = \frac{P_m \mathrm{R}_t}{\lambda v} = \frac{\frac{1}{2} C_P(\lambda)\rho\pi R^2. v_1^3 R_t}{\lambda v} = \frac{1}{2\lambda} C_P \rho\pi R_t^3. v_1^2$$

$$T_t = \frac{1}{2\lambda} C_P \rho\pi R_t^3. v^2 \qquad (3\text{-}11)$$

$$C_P = \frac{2\lambda. T_t}{\rho\pi R_t^3. v^2}$$

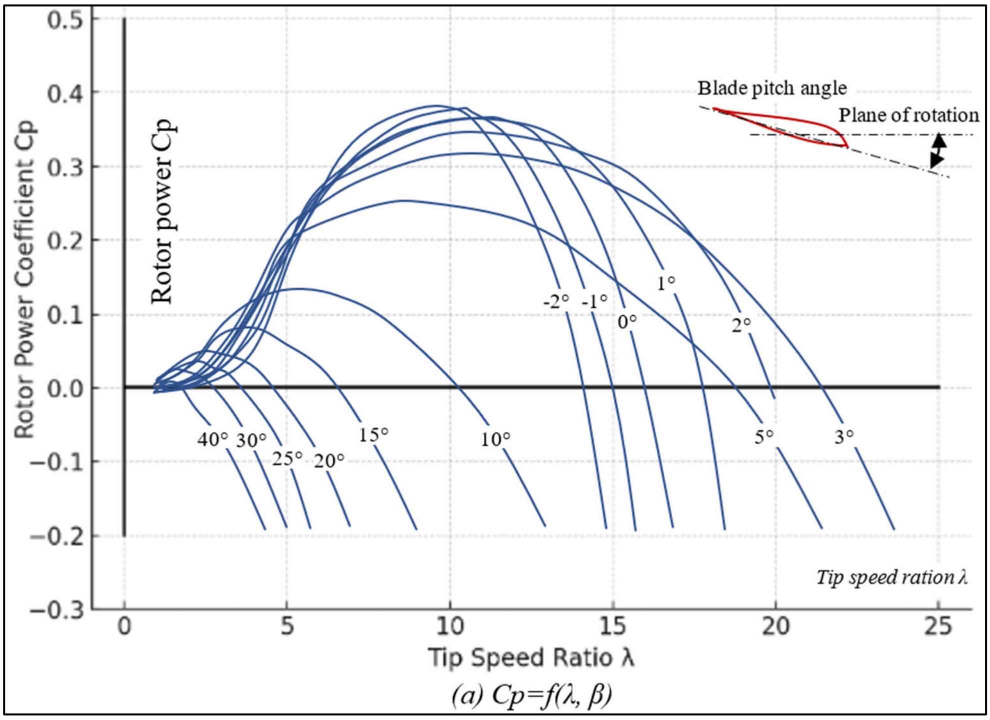
The value of the torque coefficient is determined by the following formula:

$$\mathrm{C}_m = \frac{C_P}{\lambda} = \frac{2T_t}{\rho\pi R_t^3. v^2} = \frac{2T_t}{\rho. S. R_t. v^2} \qquad (3\text{-}12)$$

Tt: Torque of the wind turbine.

6- Characteristic Curves of Wind Turbines

The essential curves characterizing wind turbines are described by the power coefficient Cp and torque coefficient Cm as functions of the specific speed λ. In general, turbines have a blade pitch control system to limit the rotation speed. Therefore, the shapes of the Cp and Cm coefficients change for each blade pitch angle β, as shown in Figure 3-4.



(a) Cp=f(λ, β)

Fig 3-4: Shapes of Cp and Cm coefficients as functions of specific speed λ and blade pitch angle

7- Mechanical Energy Production

Taking into account the gear ratio G and using equations (3.10) and (3.7), the expression for the mechanical power available on the generator's shaft can be given as:

$$P_m = \frac{1}{2} C_P \left(\frac{\Omega_t R_t}{v}\right) \rho \pi R^2 . v_1^3 \qquad (3\text{-}13)$$

This expression allows for the creation of a network of curves representing this power as a function of rotation speed for various wind speeds (Figure 3-5).

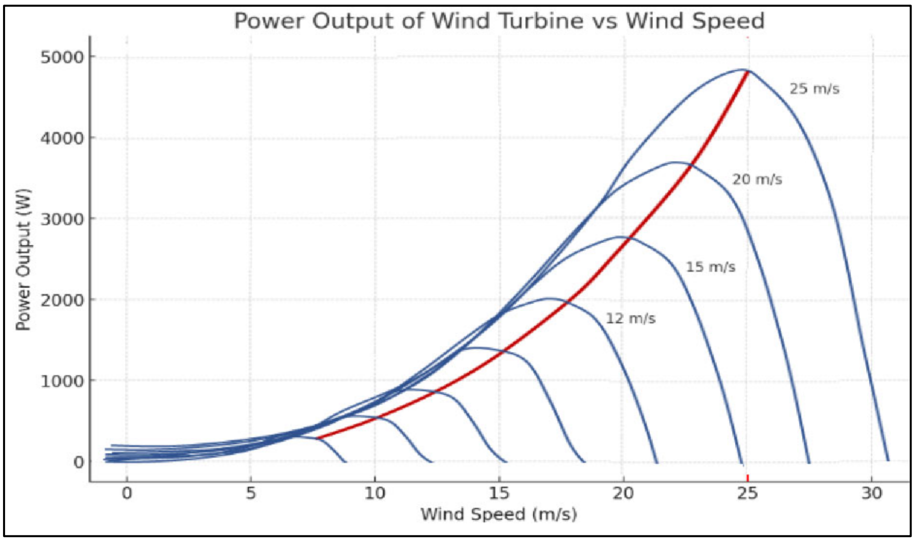


Fig 3-5: Theoretical power available as a function of wind speed

Considering the red curve marked PM, which connects the points of maximum power, it becomes apparent that in order to optimize power transfer for each wind speed, the machine must be able to operate at variable speeds.

Exercises of chapter 3

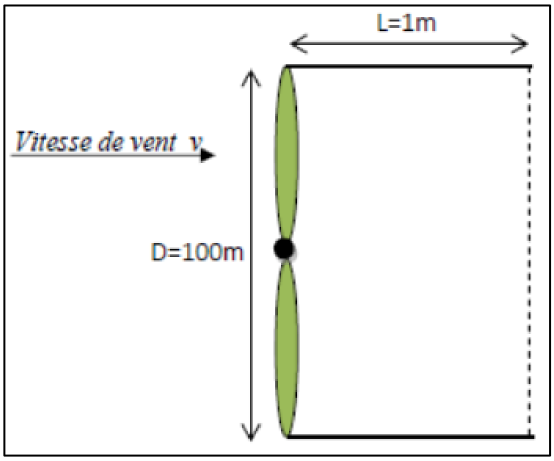
Exercise 1:

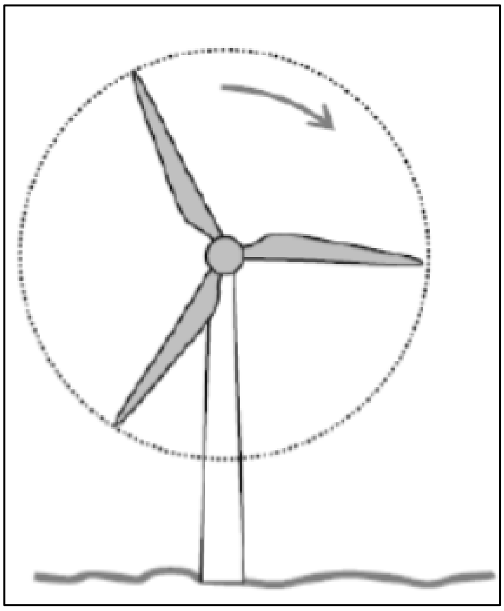
We are studying a medium-sized wind turbine with a 100m diameter under normal temperature and pressure conditions (15°C, 1013hPa). The density of dry air is ρ = 1.225 Kg/m³.

The turbine is driven by a steady wind blowing at v = 11 m/s (40 Km/h).

1. Calculate the mass m1 of an air slice of length l=1m facing the wind turbine. Deduce the mass ms passing through the blades each second.
2. Calculate the kinetic energy E_{cin} of this mass, and deduce the power of the wind P.
3. Redo the calculation using the formula: $P = \frac{1}{2}\rho V^3 \pi r^2$
4. Calculate the maximum recoverable power considering Betz's limit:

$$P_{max} = \frac{16}{27} P_{vent}$$





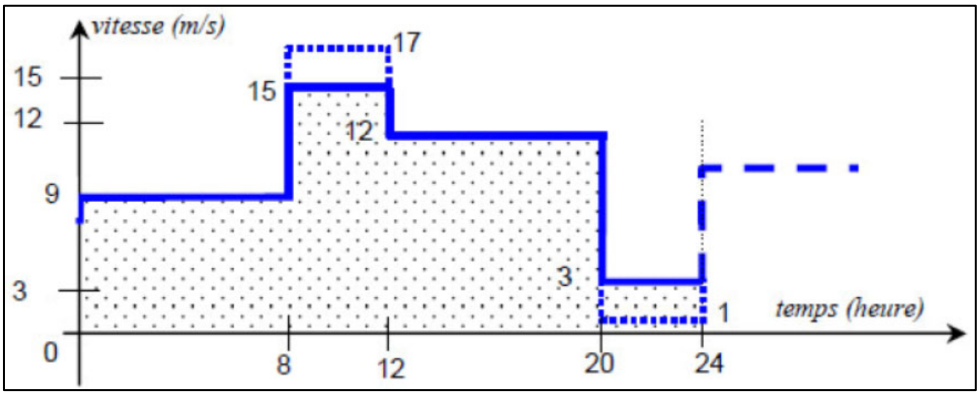
Exercise 2:

A wind blows for 24 hours following the chronogram below:

1. Calculate the average wind speed V_{moy}

2. Considering Betz's limit, calculate the maximum recoverable energy per 1m² of surface area:

- a) If the wind blew steadily at $V=V_{moy}=Cte$
- b) For the given profile.
- c) For a wind with the same average speed and profile but with $V_{min}=1m/s$ et $V_{max}=17m/s$



Exercise 3:

1. Calculate the tangential speed V_{T1} at the tip of a wind turbine blade of 100m diameter, rotating at 12 rpm.

2. Calculate the speeds V_{T2} and V_{T3} at 2/3 and 1/3 of the blade, respectively.

3. Calculate the apparent wind speeds V_{a1},V_{a2},V_{a3} and the corresponding incidence angles $\delta 1$,$\delta 2$,$\delta 3$ if the wind arrives directly facing the turbine at V=20m/s.

Note: The angle formed by the blade and the rotation plane is considered zero.

Exercises (Solutions)

Exercise 1 :

1-

$\rho = \frac{m}{V} \Rightarrow m = \rho \times V$

$V = \pi \left(\frac{D}{2}\right)^2 \times l = 3.14 \left(\frac{100}{2}\right)^2 \times 1 \quad V: Volume\ (m^3)$

$V = 7850m^3$

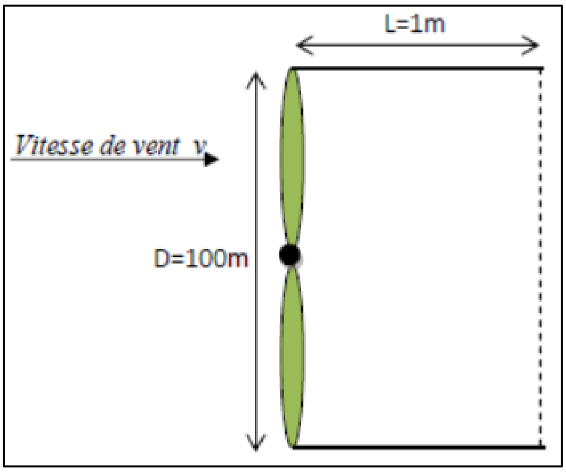
$m = \rho \times V\ = 1.255 \times 7850 = 9851.75Kg$

$m = 9851.75Kg$

$m_s = \rho \times v \times S = \rho \times v \times \pi \left(\frac{D}{2}\right)^2 \qquad v: vitess\ (m/s)$

$$m_s = \rho \times v \times \pi \left(\frac{D}{2}\right)^2 = 1.225 \times 11 \times 3.14 \left(\frac{100}{2}\right)^2 = 105\ 778{,}75Kg/s$$

$m_s = 105\ 778{,}75Kg/s$



2-Calculation of the kinetic energy of ms

$$E_{cin} = \frac{1}{2} m_s . v^2 = \frac{1}{2} \times 105\ 778{,}75 \times 11^2 = 6\ 399\ 614{,}375J$$

$E_{cin} = 6\ 399\ 614{,}375J$

$P_{vent} = E_{cin} \times t = 6\ 399\ 614{,}375 \times 1$

$P_{vent} = 6\ 399\ 614{,}375W$

3- Reproduction of the calculation using the formula:

$$P_{aero} = \frac{1}{2}\rho S_0 v^3 = \frac{1}{2}\rho\pi R^2 v^3 = \frac{1}{2}1.225 \times \pi \times 50^2 11^3 = 6\ 399\ 614{,}375$$

$$P_{aero} = 6\ 399\ 614{,}375 W$$

So, noting that: $P_{aero} = P_{vent}$

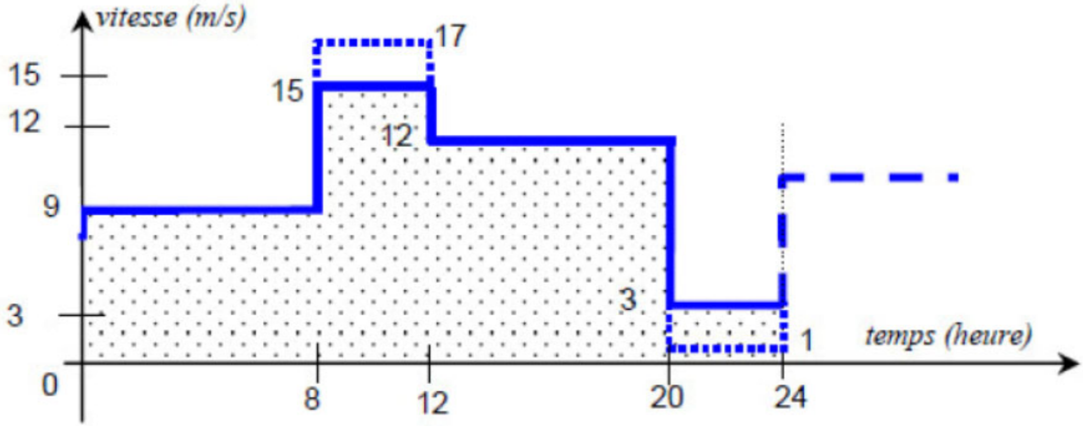
The wind speed is considered constant, so almost all the wind energy is recovered by the wind turbine.

4- Calculation of the maximum recoverable power considering that the Betz limit is equal to:

$$P_{max} = \frac{16}{27} \times P_{vent} = \frac{16}{27} \times 6\ 399\ 614{,}375$$

$$P_{max} = 3792364.074 W$$

<u>Exercise 2 :</u>



1- Calculation of the average wind speed VAvr

$$V_{Avr} = \frac{9 \times 8 \times 15 \times 4 + 12 \times 8 + 3 \times 4}{24} = 10\ m/s$$

2-Calculation of the maximum recoverable energy on 1m² of surface over the period t = 24 hours:

We have:

$$E_{max} = P_{max} \times t = \frac{16}{27} \times P_{aéro} \times t = \frac{16}{27} \times \frac{1}{2} \times \rho \times S \times V_{avr}^3 \times t$$

a)-

$$P_m = Ct = 10\,m/s$$

$$E_{max} = P_{max} \times t = \frac{16}{27} \times P_{aéro} \times t$$

$$E_{max} = \frac{16}{27} \times \frac{16}{27} \times 1.225 \times 1 \times 10^3 \times 24 \times 3600$$

$$E_{max-a} = 31462.4Kj$$

b)- Calculation of the maximum energy for the profile below:

$$E_{max} = \sum_{i=1}^{i=4} E_i = \frac{1}{2} \times \frac{16}{27} \times \rho \times S \times [v_1^3 t_1 + v_2^3 t_1 + v_3^3 t_1 + v_1^3 t_4]$$

$$E_{max} = \sum_{i=1}^{i=4} E_i = \frac{1}{2} \times \frac{16}{27} \times 1.225 \times 1 \times [9^3 \times 8 + 15^3 \times 4 + 12^3 \times 8 + 3^3 \times 4]$$

$$E_{max-b} = 43464.96Kj$$

We notice that:

$$E_{max-b} > E_{max-a}$$

This leads us to deduce that the term v³ is the most significant parameter in the value of the power and energy of the wind recovered by the wind turbine.$E_{max} = \sum_{i=1}^{i=4} E_i = \frac{1}{2} \times \frac{16}{27} \times \rho \times S \times [v_1^3 t_1 + v_2^3 t_1 + v_3^3 t_1 + v_1^3 t_4]$

$$E_{max} = \sum_{i=1}^{i=4} E_i = \frac{1}{2} \times \frac{16}{27} \times 1.225 \times 1 \times [9^3 \times 8 + 17^3 \times 4 + 12^3 \times 8 + 1^3 \times 4]$$

$$E_{max-c} = 51367.68Kj$$

We notice that:

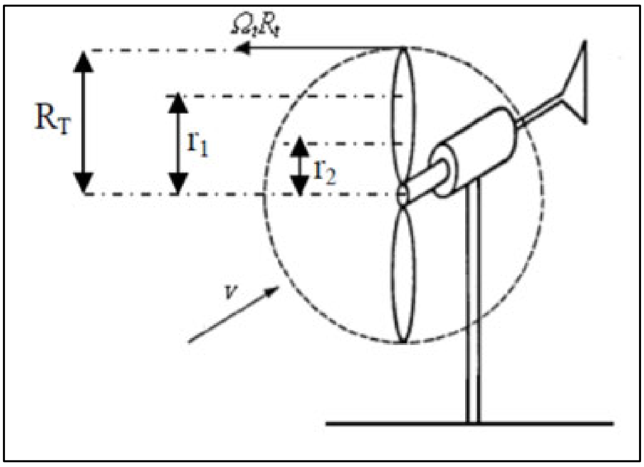
$$E_{max-c} > E_{max-b}$$

This is due to the term 17^3

Exercise 3:

The radius of the turbine:

$$\mathrm{R}_t = \frac{\phi}{2} = \frac{100}{2} = 50m$$



The rotational speed:

$$\Omega_t = 12\frac{tr}{mn} = \frac{12.\pi}{30} rd/s$$

1- Calculation of the tangential speed v_{T1} at the tip of the blade:

$$v_{T1} = \Omega_r \times R_t = \frac{12.\pi}{30} \times 50 = 62.8\, m/s$$

2- Calculation of v_{r2} and v_{r3}:

$$v_{T2} = \Omega_r \times r_1 = \Omega_r \times \frac{2}{3} R_t = \frac{2}{3} v_{T1} = 41.86\, m/s$$

$$v_{T3} = \Omega_r \times r_2 = \Omega_r \times \frac{1}{3} R_t = \frac{1}{3} v_{T1} = 20.93\, m/s$$

3- Calculation of the apparent wind speeds and the angles of incidence δ_i :

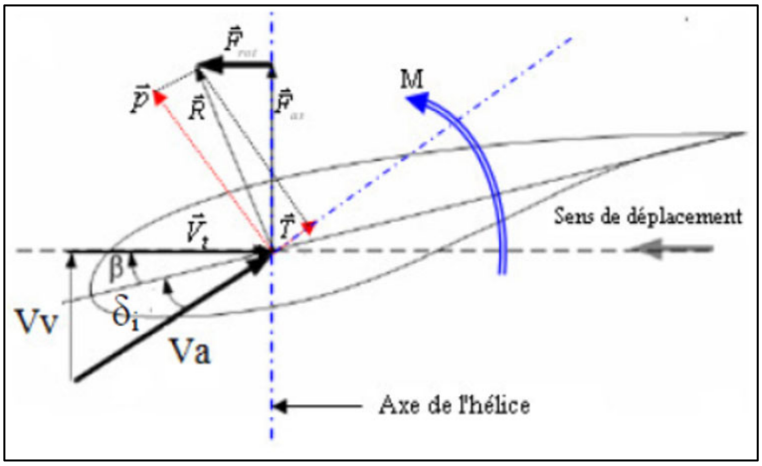
We have:

$$V_a = \sqrt{V_v^2 + V_T^2}$$

$$V_{a1} = \sqrt{V_v^2 + V_{T1}^2} = \sqrt{20^2 + 62.8^2} = 63.93 m/s$$

$$V_{a2} = \sqrt{V_v^2 + V_{T2}^2} = \sqrt{20^2 + 41.86^2} = 43.54 m/s$$

$$V_{a3} = \sqrt{V_v^2 + V_{T3}^2} = \sqrt{20^2 + 20.93^2} = 24.126 m/s$$



Calculation of the angles of incidence:

Since the setting angle $\beta = 0°$, we have:

$$\delta_i = arctg\frac{V_v}{V_T}$$

Consequently:

$$\delta_{i1} = arctg\frac{V_v}{V_{T1}} = arctg\frac{20}{62.8} = 17.66°$$

$$\delta_{i2} = arctg\frac{V_v}{V_{T2}} = arctg\frac{20}{41.86} = 25.53°$$

$$\delta_{i3} = arctg\frac{V_v}{V_{T3}} = arctg\frac{20}{20.93} = 43.7°$$

Chapter 4: Modeling and Simulation of the Mechanical System of Wind Turbines

1- Components of a wind turbine

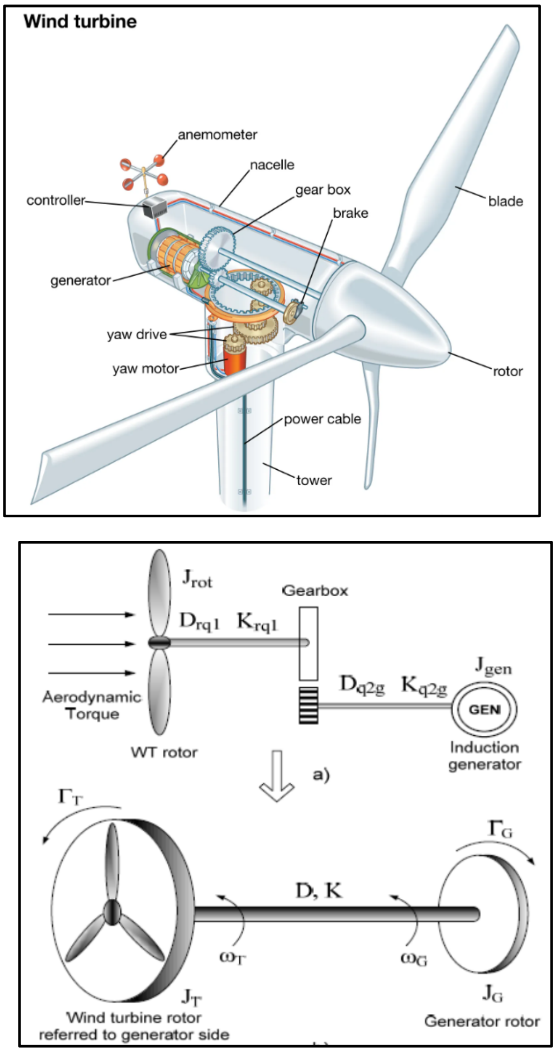


Fig 4-1 : Components of a wind turbine.

The components of a wind turbine are as follows:

1-1- Tower (or Mast):

The tower is the vertical structure that supports the wind turbine. It is typically made of steel and can reach great heights to capture stronger and more consistent winds.

1-2- Rotor:

The rotor is the rotating part of the wind turbine that captures wind energy. It consists of blades attached to a central hub. The number of blades may vary, but three blades are common.

1-3- Blades:

Blades are aerodynamic wings that capture the wind. They are designed to convert the kinetic energy of the wind into rotational motion. Materials used for blades include fiberglass, carbon composite, or aluminum.

1-4- Hub:

The hub is the central piece to which the blades are attached. It transfers the rotational motion of the blades to the generator shaft.

1-5- Generator Shaft:

The generator shaft transmits the rotational motion from the hub to the generator. It is typically connected to the generator through a gearbox to optimize the rotation speed.

1-6- Generator:

The generator is the component that converts mechanical energy into electrical energy. It uses the rotational motion to generate electricity, usually employing a synchronous or asynchronous generator.

1-7- Control System:

Wind turbines are equipped with sensors and advanced control systems to monitor wind speed, blade orientation, and other parameters. These systems automatically adjust the blade angle to optimize energy production and protect the wind turbine from extreme weather conditions.

1-8- Braking System:

For safety reasons, wind turbines are equipped with braking systems to stop the rotor's rotation when necessary, such as during storms or for maintenance.

1-9- Nacelle:

The nacelle is a structure located at the top of the tower that houses the generator, gearbox, control system, and other essential components. It is designed to rotate to align the blades with the wind.

1-10- Foundation:

The foundation is the concrete or steel structure buried in the ground that supports the tower. It ensures the stability of the wind turbine.

1-11- Transformer:

Once electricity is generated, it is typically passed through a transformer to increase the voltage for easier transmission over long distances.

2- Turbine Modeling

2-1. La The wind power or wind turbine power:

$$P_v = \frac{1}{2}.\rho.S.v^3 \qquad (4\text{-}1)$$

2-2. Turbine power :Pt

$$C_P = \frac{P_t}{P_v} \Rightarrow$$

$$P_t = C_P \times P_v \quad \text{Et} \quad P_t = C_t \times \Omega_t \quad \text{aussi}$$

$$P_t = \frac{1}{2}C_P.\rho.S.v^3 \qquad (4\text{-}2)$$

(Cp is provided in Appendix 3)

With:

$C_P(\lambda, \beta)$

$\lambda = \frac{\Omega_t R_t}{v}$

$S = \pi R_t^2$

R_t $(Turbine\ radius)$

3- Modeling of the gearbox:

$$\Omega_{mec} = G.\Omega_t \qquad (4\text{-}3)$$

$$C_g = \frac{1}{G}.C_t \qquad (4\text{-}4)$$

Ω_{mec} $(Output\ angular\ velocity\ of\ the\ gearbox\ )$

Ω_t $(Output\ angular\ velocity\ of\ the\ turbine)$

G $(Multiplication\ ratio)$

C_g $(Gearbox\ torque)$

C_t $(Turbine\ torque)$

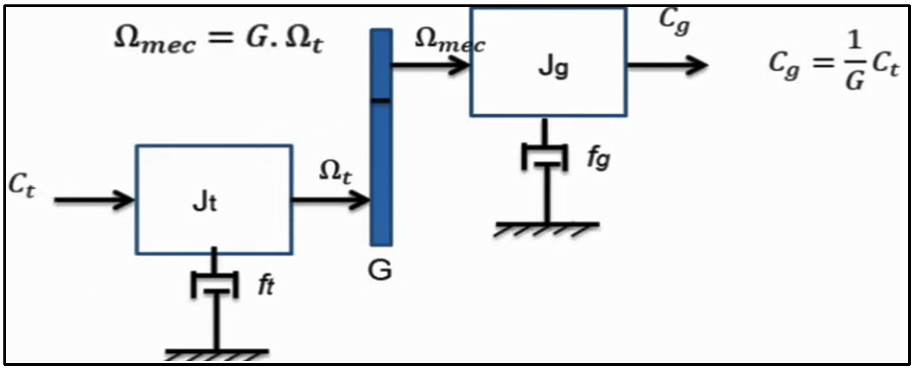


Fig 4-2 : gearbox model.

4- Modeling of the mechanical shaft

Our goal is to find the angular velocity of the mechanical shaft $\boldsymbol{\Omega_{mec}}$ that enters the electrical generator.

$$J_{total} = J_g + G^2 \times J_t \qquad (4\text{-}5)$$

J_{total}	$(Total\ moment\ of\ inertia)$
J_g	$(Moment\ of\ inertia\ of\ the\ generator)$
G	$(Multiplication\ ratio)$
J_t	$(Moment\ of\ inertia\ of\ the\ turbine)$

$$C_{total} = J_{total} \times \frac{d\Omega_{mec}}{dt} \qquad (4\text{-}6)$$

C_{total}	$(Total\ mechanical\ torque)$
Ω_{mec}	$(Output\ angular\ velocity\ of\ the\ gearbox)$

$$C_{total} = C_g - C_{em} - C_f = J_{total} \times \frac{d\Omega_{mec}}{dt} \qquad (4\text{-}7)$$

C_{total}	$(Total\ mechanical\ torque)$	
C_g	$(Turbine\ mechanical\ torque)$	
C_{gem}	$(Electromagnetic\ torque)$	
C_f	$(Frictional\ torque)$	$C_f = f \times \Omega_{mec}$

$$C_{total} = C_g - C_{em} - f \times \Omega_{mec} = J_{total} \times \frac{d\Omega_{mec}}{dt}$$

$$\frac{d\Omega_{mec}}{dt} = S \times \Omega_{mec}$$

$$C_{total} = C_g - C_{em} - f \times \Omega_{mec} = J_{total}.S \times \Omega_{mec} \qquad (4\text{-}8)$$

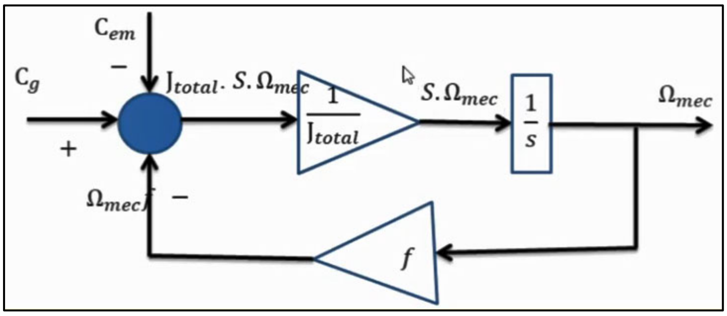


Fig 4-3: Output angular velocity (First method)

Another method:

$$C_{total} = C_g - C_{em} - f \times \Omega_{mec} = J_{total}.S \times \Omega_{mec}$$

$$C_g - C_{em} = f \times \Omega_{mec} + J_{total}.S \times \Omega_{mec}$$

$$C_g - C_{em} = (f + J_{total}.S)\Omega_{mec}$$

$$\Omega_{mec} = (C_g - C_{em}).\frac{1}{J_{total}.S+f} \quad (4\text{-}9)$$

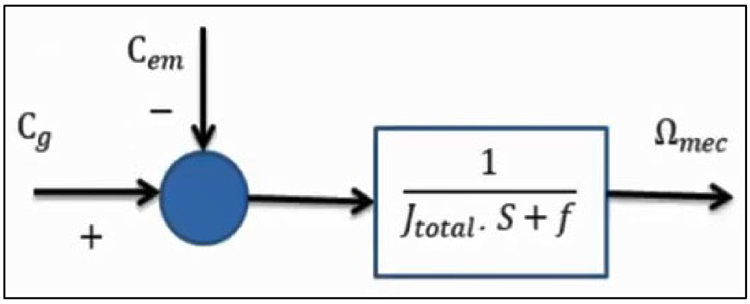


Fig 4-4 :Out put angular velocity (second method)

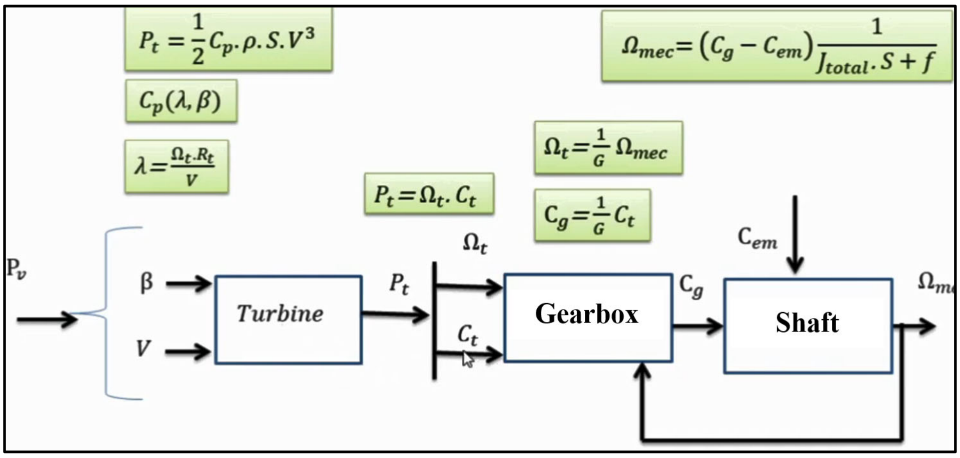


Fig 4-5: Modeling of the turbine

Simplifying Assumptions:

- ☐ The blades are considered to be identical in design with the same parameters of inertia, elasticity, and friction.
- ☐ The coefficients of friction of the blades with respect to the air and with respect to the support are very low and can be ignored.
- ☐ The wind speed is assumed to be uniformly distributed across all the blades, allowing us to consider the entire set of blades as a single mechanical system characterized by the sum of all the mechanical systems.

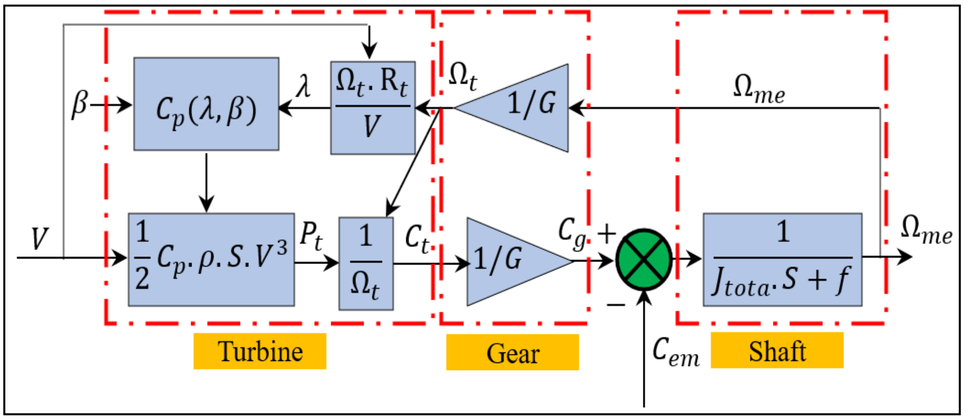


Fig 4-6 : turbine simulation

The Simulink diagram

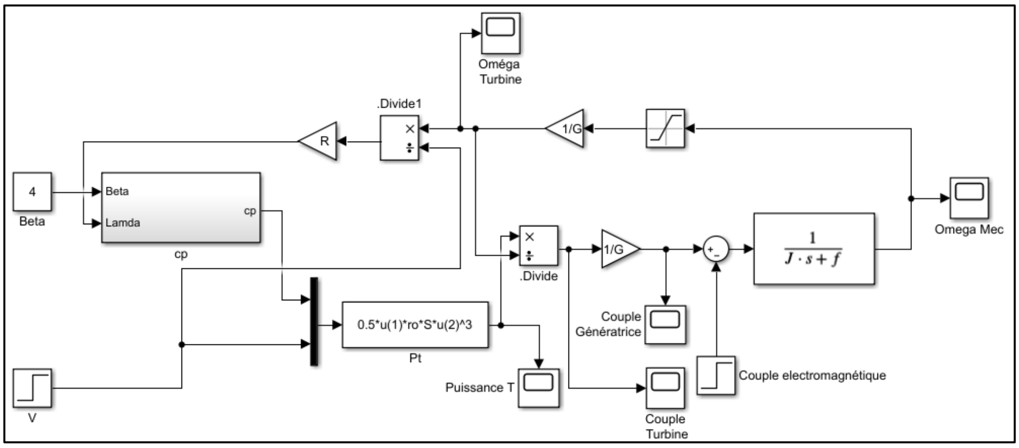


Fig 4-7 : Simulink diagram of the turbine simulation

Some results

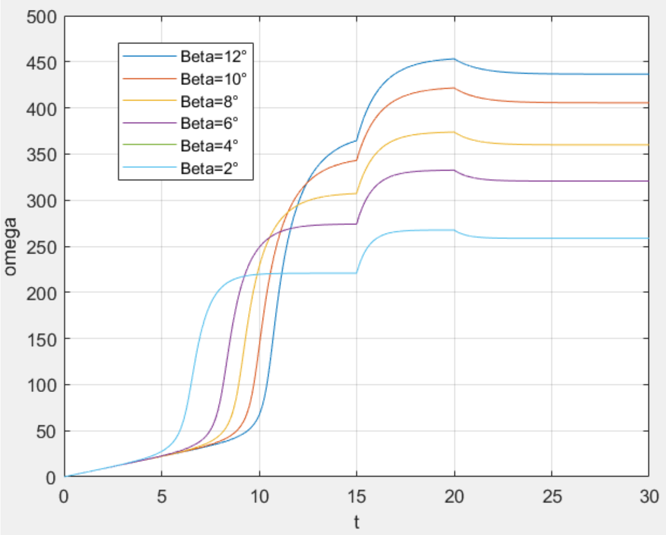


Fig 4-8: Output angular velocity for different Beta:

Parameters of simulation:

```
clc
J=0.21
f=0.0001
R=3
G=6
ro=1.22
S=pi*R^2
```

Exercises of chapter 4

Exercise 1:

The recoverable power **P (in Watts)** from a wind turbine is given by the formula: $P=0.14 x D^2 x V^3$ where **D** is the diameter in meters and **V** is the wind speed in m/s.

1. Justify this formula. Compute the power coefficient of the wind turbine.
2. Calculate the recoverable power in MW for an offshore wind turbine with a 125m diameter, when the wind blows at 12 m/s.
3. Calculate the mass of air passing through the wind turbine per second and express the result in terms of elephants.
4. The first wind turbine installed in France (at Port-la-Nouvelle, Aude) in 1991 had a diameter of 25m. By what factor is the power multiplied when switching to a diameter of 125m?
5. For a fixed diameter, by what factor is the power multiplied when the wind speed is doubled?

Exercise 2:

Calculate the exit diameter **Φs** of the "air tube" downstream of a wind turbine with an initial diameter **Φ**, as a function of the wind speed **V1** when **Betz's limit** is reached:

$P_{max} = \frac{16}{27} P_{vent}$ with $V_2 = \frac{1}{3} V_1$

Exercises (Solutions)

Exercise 1 :

The recoverable power from a wind turbine is given by:

$$P = 0.14 \times D^2 \times v^3$$

1. Justification of the formula:

Using the general formula for wind power:

$$P = \frac{1}{2}\,.\rho.Cp.S.v^3$$

where:

$$S = \pi.R^2 = \frac{\pi}{4}D^2$$

By comparison:

$P = \frac{1}{2}\,.\rho.Cp.S.v^3 = \frac{1}{2}\,.\rho.Cp.\frac{\pi}{4}D^2.v^3 = k.D^2.v^3$, $P = k.D^2.v^3$ where:

$k = \frac{1}{2}\,.\rho.Cp.\frac{\pi}{4}$

Thus:

$$Cp = \frac{8.k}{\rho.\pi} = Cp = \frac{8 \times 0.14}{1.225 \times \pi} = 0.29$$

2. Power calculation:

$P = k.D^2.v^3 = 0.29 \times 125^2 \times 12^3$,

$P = 3.78\,Mw$

3. Mass of air passing through the wind turbine per second:

$$\frac{\Delta m}{\Delta t} = \rho.S.v = 1.225 \times \frac{\pi}{4} \times 125^2 \times 12 = 180.69\,Kg/s$$

4. Power increase when diameter changes from 25m to 125m:

$D_1 = 25m \quad P_1 = \frac{1}{2}\,.\rho.Cp.S_1.v^3$

$D_2 = 125m \quad P_2 = \frac{1}{2}\,.\rho.Cp.S_2.v^3$

Thus:

$$\frac{P_2}{P_1} = \frac{\frac{1}{2}.\rho.Cp.S_2.v^3}{\frac{1}{2}.\rho.Cp.S_1.v^3} = \frac{S_2}{S_1} = \frac{\frac{\pi}{4}{D_2}^2}{\frac{\pi}{4}{D_1}^2} = \frac{{D_2}^2}{{D_1}^2} = \left(\frac{D_2}{D_1}\right)^2 = \left(\frac{125}{25}\right)^2 = 25$$

$\frac{P_2}{P_1} = 25$

Then :

$P_2 = 25P_1$

5. $\begin{cases} P_1 = \frac{1}{2} \,.\rho.Cp.S_1.{v_1}^3 \\ P_2 = \frac{1}{2} \,.\rho.Cp.S_1.{v_2}^3 \end{cases}$

Donc : $\frac{P_1}{P_2} = \frac{\frac{1}{2}.\rho.Cp.S_1.{v_1}^3}{\frac{1}{2}.\rho.Cp.S_1.{v_2}^3} = \frac{{v_1}^3}{{v_2}^3} = \left(\frac{v_1}{v_2}\right)^3$

$$\frac{P_2}{P_1} = \left(\frac{v_2}{v_1}\right)^3 = 2^3 = 8$$

Exercise 2 :

Knowing that the mass flow rate is constant upstream and downstream of the wind turbine:

$$\frac{\Delta m}{\Delta t} = \rho.S_1.v_1 = \rho.S_2.v_2$$

Therefore:

$S_2 = S_1 \frac{v_1}{v_2} = S_1 \times 3$

$$\frac{\pi}{4} \times {\phi_s}^2 = 3 \times \frac{\pi}{4} \times \phi^2$$

Then:

$\phi_s = \sqrt{3}\phi$

Chapter 5 : Topologies of Wind-Energy Systems

1- Introduction

The study of wind-energy system topologies represents a fundamental step in understanding how mechanical energy from the wind is efficiently transformed into electrical energy. This chapter focuses on the principal configurations, machines, and conversion technologies used in modern wind turbines. It presents an overview of the electromechanical conversion process, comparing fixed-speed and variable-speed operations, and highlights the advantages and limitations of each approach.

By exploring both synchronous and asynchronous generators, including advanced architectures such as the Doubly-Fed Induction Generator (DFIG) and the Permanent Magnet Synchronous Generator (PMSG) this chapter aims to provide a comprehensive understanding of the different topologies that underpin reliable and efficient wind-energy conversion. Furthermore, the integration of power-electronic converters and their role in grid connection is discussed as a key component in optimizing energy quality and control.

2- State of the Art in Electromechanical Conversion

The electrical configuration of a wind generator has a major influence on its operation. Whether a wind turbine runs at **fixed** or **variable** speed depends on this configuration. Their main advantages and drawbacks are summarized below.

2-1. Fixed-Speed Operation

Advantages

1. Simpler electrical system
2. Lower cost
3. No need for electronic control equipment
4. Higher reliability and less maintenance

Disadvantages

1. Captured energy is not always optimal
2. Difficult control of the power injected into the grid
3. Mechanical torque oscillations within the drivetrain

2-2. Variable-Speed Operation

Main Advantages

1. Optimization of captured energy thanks to rotor-speed control
2. Control of power transfer and high-quality energy delivered to the grid
3. Reduced mechanical stress: gusts and turbulence are absorbed by the turbine's inertia, decreasing torque oscillations

4. Better quality of generated electrical power
5. Simpler pitch-angle control system thanks to higher control-loop time constant
6. Lower acoustic noise

Disadvantages

1. Requires special machines
2. Higher additional cost (converters, control system, etc.)
3. Complexity of the power converters used
4. More difficult power-flow management between converters and optimum-power tracking

3- Generators and Topologies

The two main machine families used in wind-energy systems are **synchronous** and **asynchronous** (induction) machines, each with several variants.

3-1. Synchronous Generator

3-1.1. Wound-Rotor Synchronous Generator

This machine type is widely used in conventional large-scale power plants (thermal, hydro, nuclear).

The rotor field must rotate at the same speed as the stator field, so when directly grid-connected its mechanical speed is locked to the grid frequency.

Because of that, a gearbox is required to adapt turbine speed to the high generator speed. While synchronous machines can provide large torques for their size, the rigid coupling between generator and grid causes torque fluctuations from the turbine to propagate through the entire power chain, deteriorating power quality.

Therefore, such generators are rarely connected directly to the grid in wind turbines; instead, they require a power-electronic interface between the stator and the grid, enabling variable-speed operation.

Regular maintenance of slip-ring brushes is necessary, and excitation circuits are supplied via a rectifier connected to the grid.

Thus, isolated sites need an independent DC source or capacitor bank.

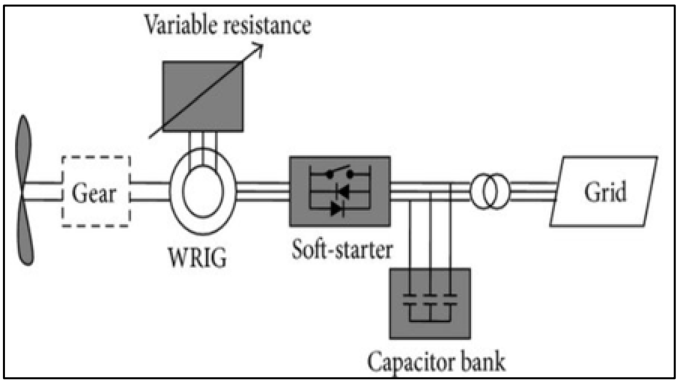


Fig 5-1: Wind system based on wound rotor synchronous machine and PWM converter

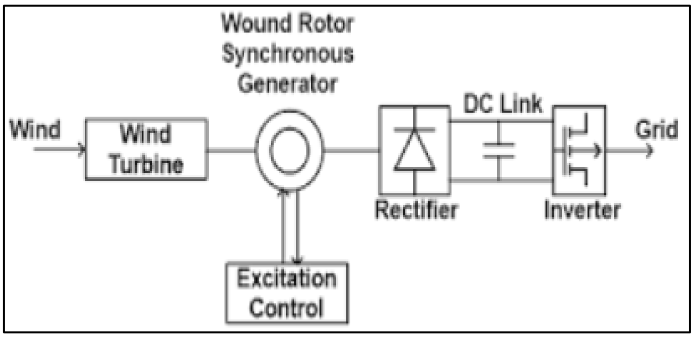


Fig 5-2: Wind system based on the wound-rotor synchronous machine and diode rectifier

3-1.2. Permanent-Magnet Synchronous Generator (PMSG)

Advances in magnetic materials have made permanent-magnet synchronous machines cost-competitive.

They feature a high number of poles and can deliver large torque, with configurations such as:

- Radial-flux (standard) machines
- Axial-flux “disc” generators
- Outer-rotor designs

Coupling PMSGs with modern power electronics is now economically viable, making them serious competitors to doubly-fed induction generators (DFIGs).

They have low failure rates because gearboxes and slip-rings are eliminated, minimizing maintenance, especially valuable for offshore applications.

The mandatory power-electronic interface allows efficient speed regulation and energy optimization.

Main Drawbacks

- High cost of rare-earth magnets

- Possible demagnetization under large electromagnetic-torque variations, shortening lifespan

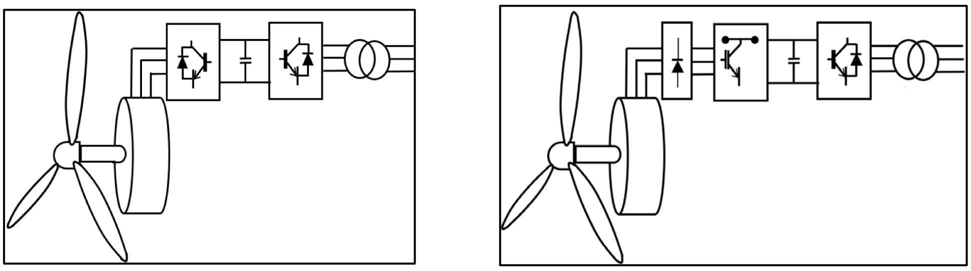


Fig 5-3: Wind systems based on the permanent magnet synchronous machine.
(a) PMSG + PWM converters,
(b) PMSG + diode rectifier + DC chopper + PWM inverter.)

The DC chopper controls electromagnetic torque, while the grid-side inverter regulates DC-bus voltage and power factor.

The diode-rectifier version suits small-power (< 50 kW) systems; the PWM-rectifier version, with vector control, allows operation near the optimum power point but depends on accurate parameter knowledge (temperature, frequency).

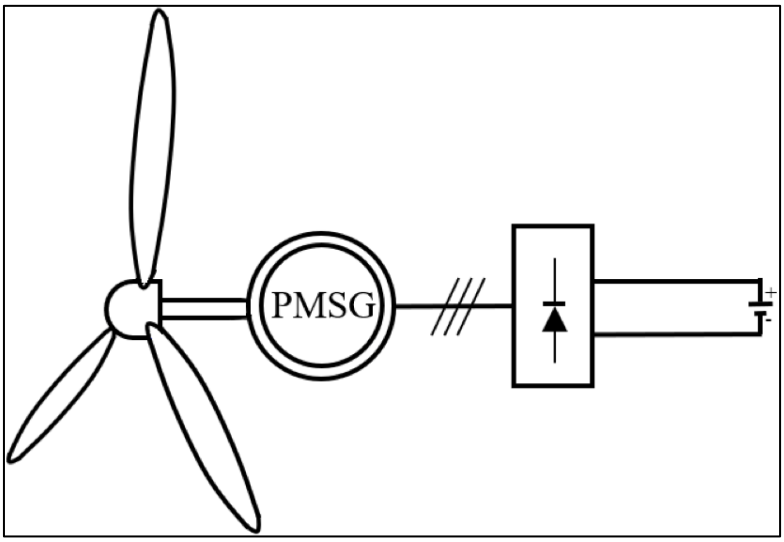


Fig 5-4: Low-cost wind-energy system based on the PMSG

3-2. Asynchronous (Induction) Generator

The **squirrel-cage induction generator (SCIG)** equips most wind turbines worldwide due to its robustness and low investment cost, especially in direct-grid-connection configurations. Though mainly used as a motor, it operates equally well as a generator and withstands harsh environments.

It is inexpensive, standardized, mass-produced over a wide power range, requires little maintenance, and has a low failure rate.

However, low rotor speed in large turbines necessitates a mechanical speed multiplier (gearbox).

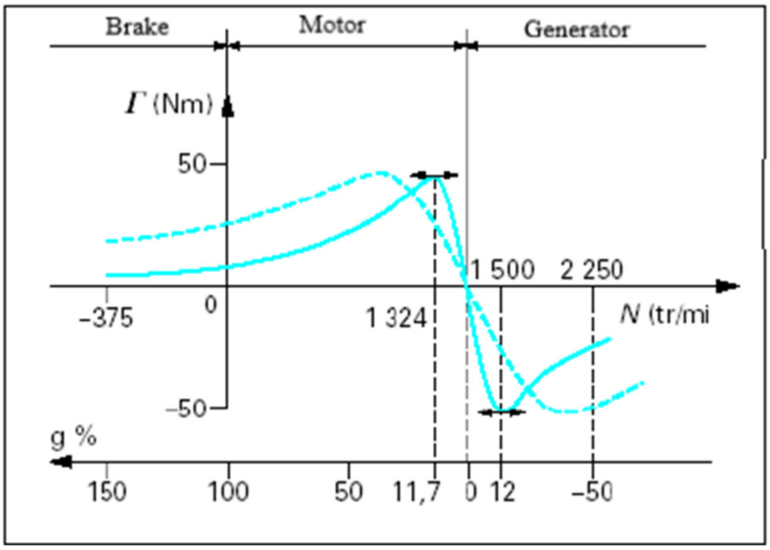


Figure 5-5: Torque–speed characteristics of an induction machine with 2 pole pairs

3-2.1. SCIG Connected to the Grid via a Rectifier–Inverter Link

(Figure 5-6) depicts this configuration.

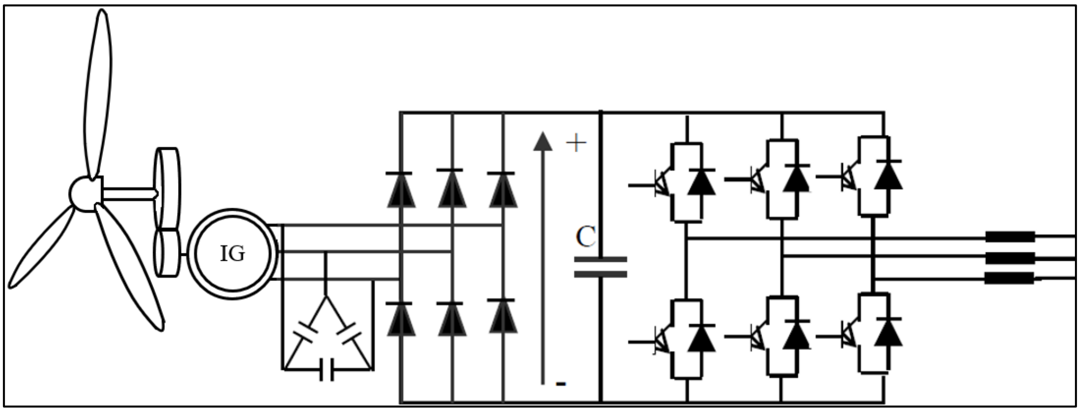


Figure 5-6: Squirrel-cage induction generator connected to the grid through a rectifier inverter set;

It allows unrestricted variable-speed operation: generator output is rectified to DC, then inverted to AC at fixed grid frequency.

Converters must handle the full machine power, adding cost and losses (≈ 3 %), and injecting harmonics.

Capacitors are required to supply magnetizing reactive power, since the diode rectifier is unidirectional.

3-2.2. SCIG with PWM Converters

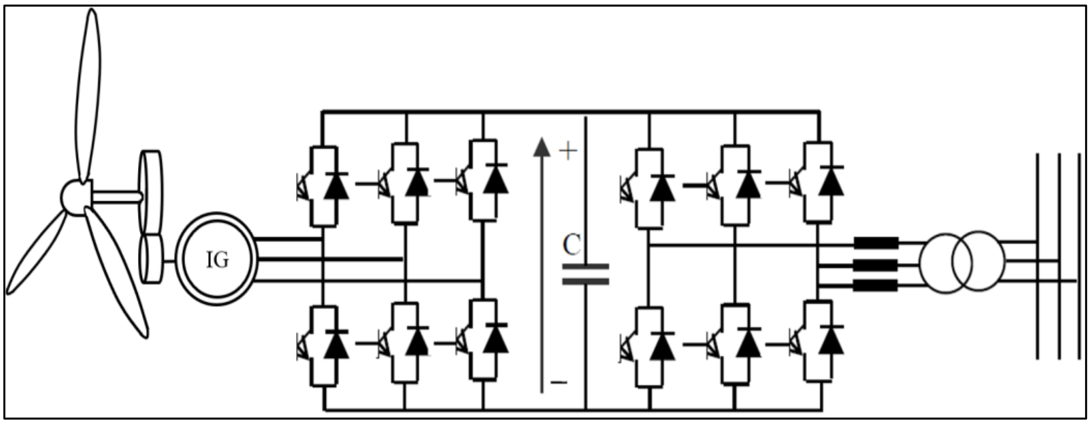


Figure 5-7: Squirrel-cage asynchronous wind generator with PWM converters;

Introducing PWM rectifier–inverter stages (Figure 5-7) decouples grid frequency from rotor speed, enabling variable-speed operation.

Reactive-power flow can be controlled through the DC link.

However, this increases system cost and complexity.

3-2.3. Direct-Grid-Connected SCIG

About **85 %** of wind turbines operate at constant speed with direct grid connection (Figure 5-8).

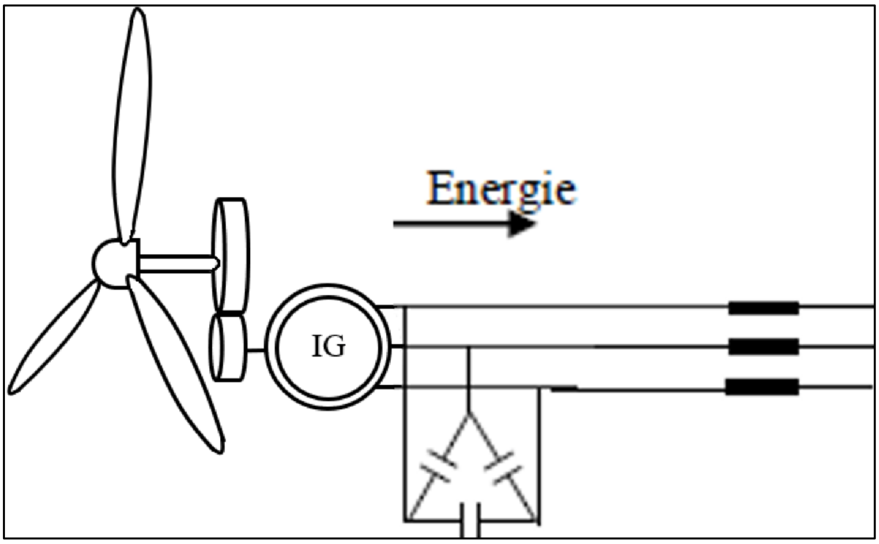


Figure 5-8: Wind system based on a squirrel-cage induction generator directly connected to the grid

The simple configuration (no converter, no slip-rings) minimizes maintenance but consumes reactive power, degrading the grid power factor.

Adding shunt capacitors compensates magnetizing reactive power, essential for isolated operation.

3-2.4. Double-Stator Induction Generator

To improve efficiency, some designs use a **dual-stator** configuration (Figure 5-9): one low-power, high-pole stator for low-wind speeds, and one high-power, low-pole stator for strong winds.

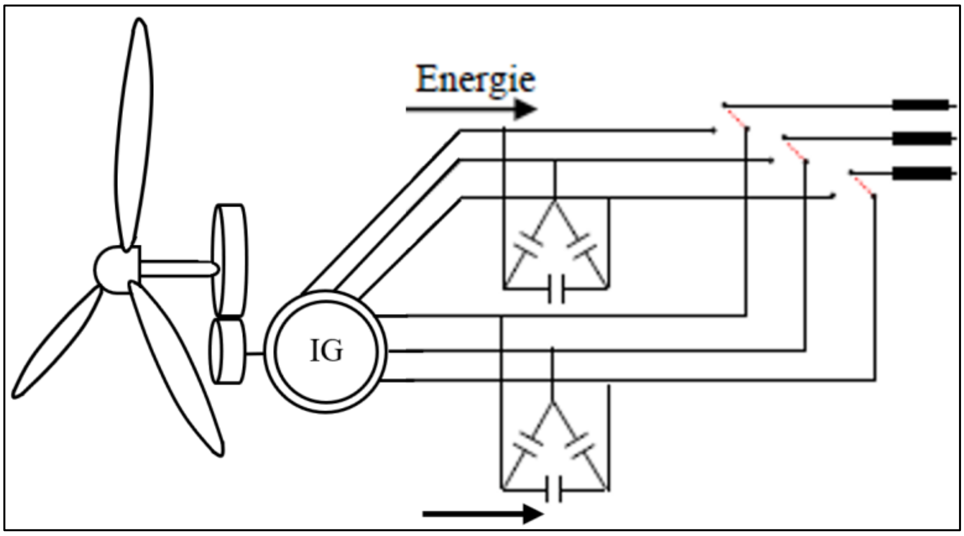


Figure 5-9: Wind system based on a double-stator induction generator

This still yields quasi-fixed speed with two operating points, reducing noise at low wind speeds. However, a second stator increases cost, diameter, weight, and bulk.

3-2.5. Wound-Rotor Induction Generator with Rotor-Resistance Control

A wound-rotor induction generator (Figure 5-10) allows limited variable-speed operation (~ ±10 %).

Rotor resistance is varied electronically via a power converter controlling slip.

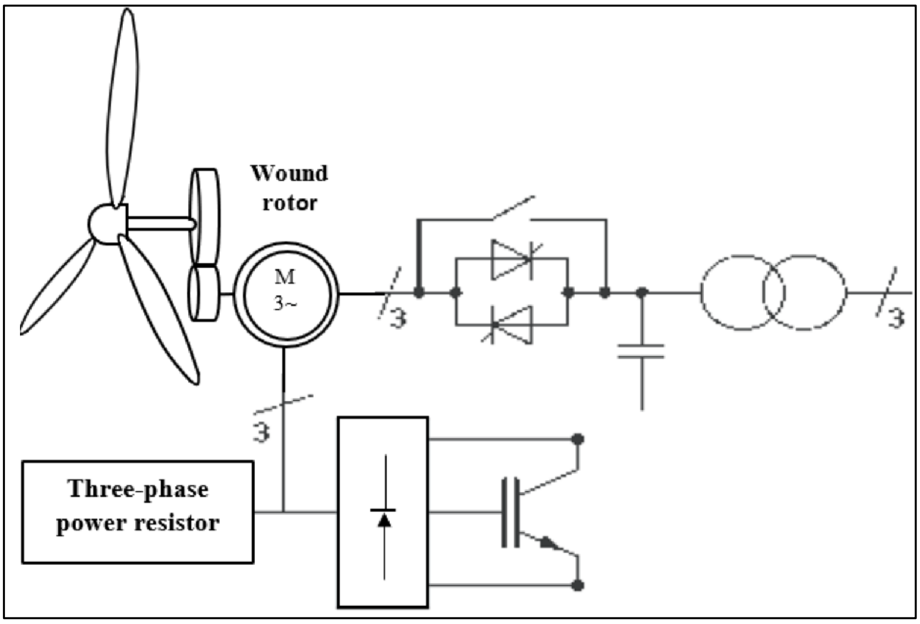


Figure 5-10: Wound-rotor asynchronous wind generator with rotor resistance control

Although electromagnetic efficiency decreases, total turbine-generator efficiency improves slightly.

A diode rectifier and chopper regulate rotor resistance by duty-cycle control of a power transistor.

3-2.6. Doubly-Fed Induction Generator (DFIG)

The doubly-fed induction generator (DFIG)—wound-rotor induction machine, is one of the two dominant variable-speed wind-energy solutions (the other being PMSG).

It has a three-phase stator connected to the grid and a three-phase rotor connected through slip-rings to a power converter.

Though slightly less robust than cage machines, its variable-speed capability (±30 %) makes it attractive to major manufacturers (Vestas, Gamesa …).

Nominal speed is somewhat lower, so the gearbox ratio can be smaller.

3-2.7. DFIG with Dissipative Rotor-Energy Control

In the configuration of Figure 5-11, the stator connects directly to the grid, while the rotor feeds a rectifier with a resistive load controlled by a chopper.

By adjusting the chopper duty ratio, the slip and thus rotor power dissipation is varied, permitting ≈ ±10 % speed variation around synchronism.

Drawback: energy losses in resistors.

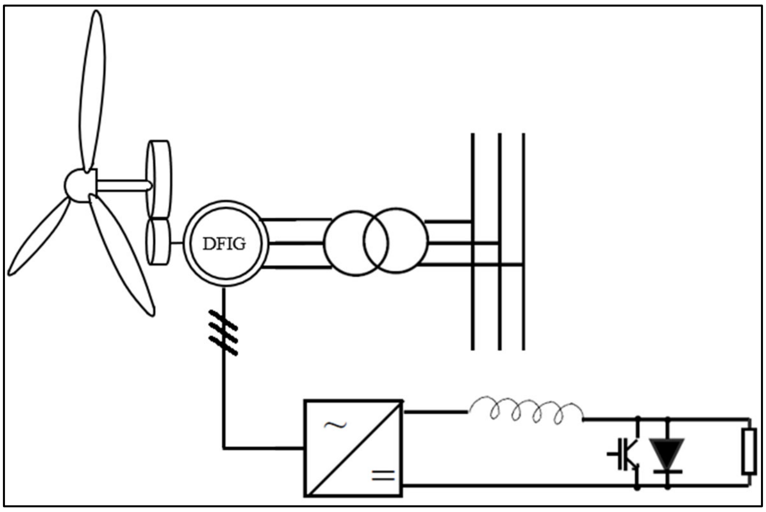


Figure 5-11: DFIG with slip control by dissipated energy

3-2.8. DFIM Kramer Drive

To avoid dissipating rotor power, the resistor–chopper set is replaced by a back-to-back rectifier/inverter (Figure 5-12) returning slip energy to the grid (Kramer system). Converters are rated for only a fraction (≈ 1/3–1/4) of machine power, reducing cost and losses.

Because the rectifier is unidirectional, energy can flow only from rotor to grid, i.e. for super-synchronous operation.

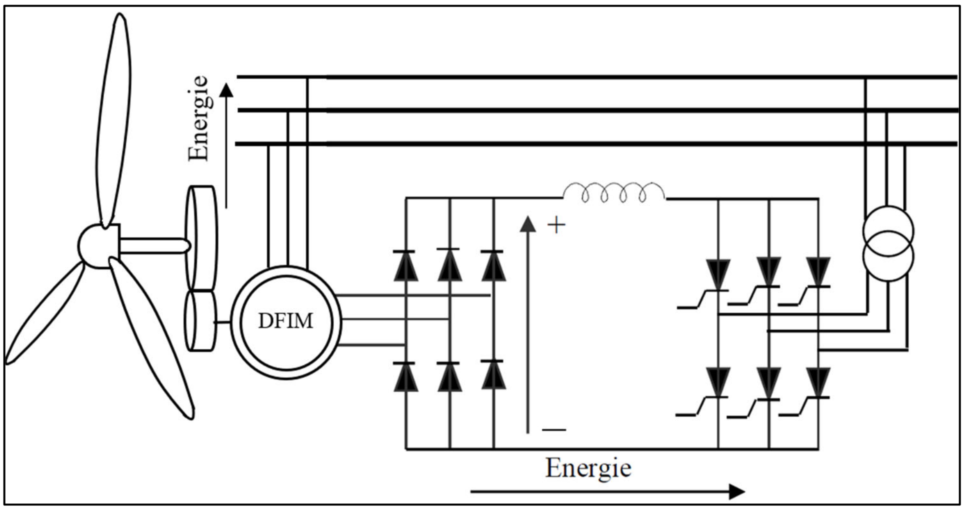


Figure 5-12: DFIM, Kramer structure

3-2.9. DFIG – Scherbius System with Cycloconverter

Replacing the rectifier/inverter by a cycloconverter (Figure 5-13) allows bidirectional power flow between rotor and grid (sub- or super-synchronous speeds).

This arrangement is called the Scherbius system.

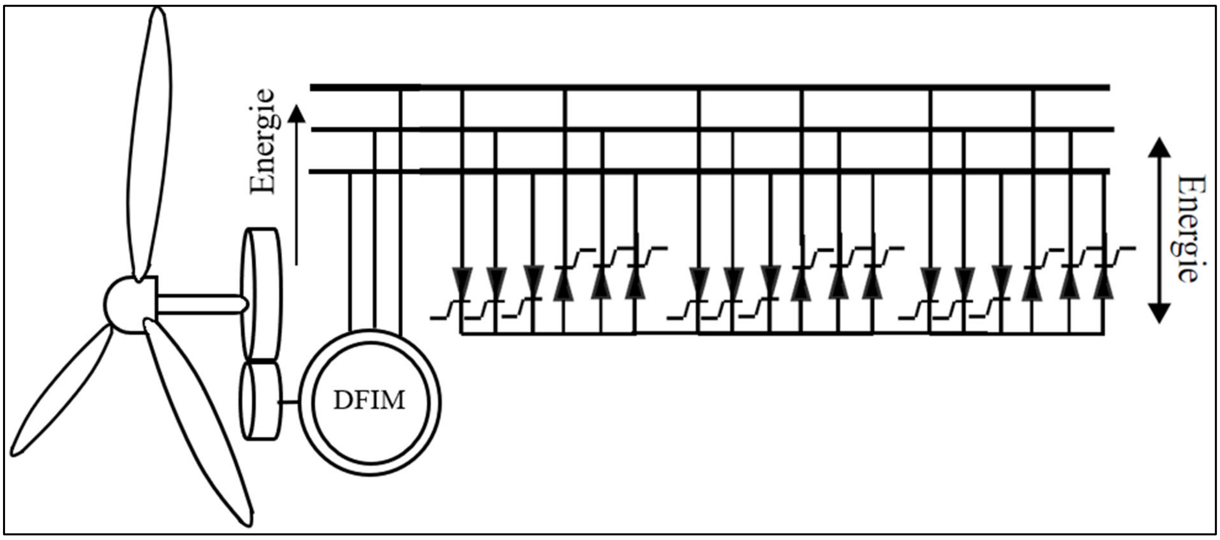


Figure 5-13: DFIM, Scherbius structure with cycloconverter

3-2.10. DFIG with PWM Converters

In modern systems (Figure 5-14), the rotor is linked to the grid through two three-phase PWM converters in back-to-back configuration (one rectifier, one inverter).

Typically, the rotor-side converter is rated for 25–33 % of stator nominal power, sufficient for ±30 % speed variation.

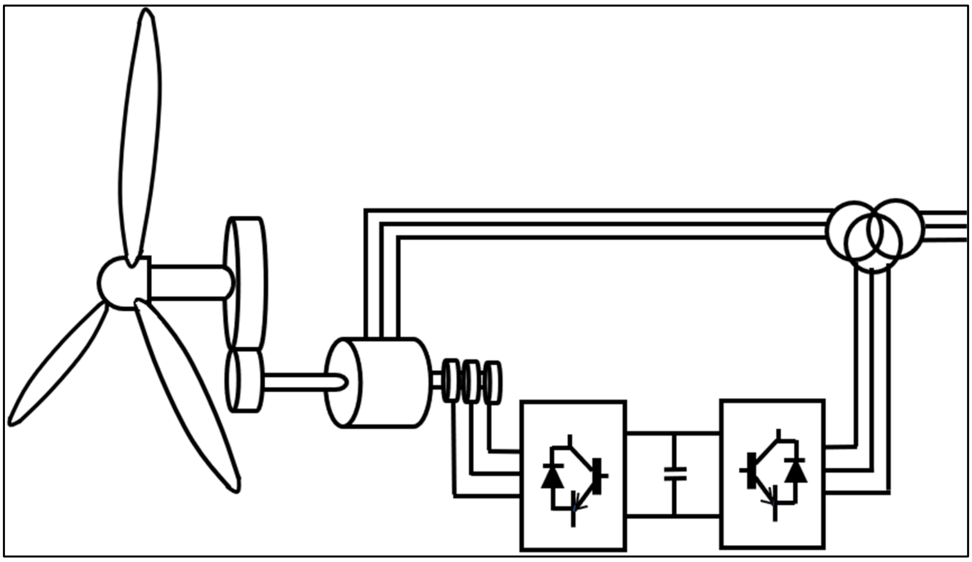


Figure 5-14: DFIG, Scherbius structure with PWM converters

Its main drawback is sensitivity to grid disturbances (voltage dips).

Nevertheless, numerous studies and industrial realizations confirm the viability of this topology for variable-speed wind turbines.

4- Summary

(Figure 5-15) synthesizes the various electrical configurations designed for converting mechanical energy into electrical energy.

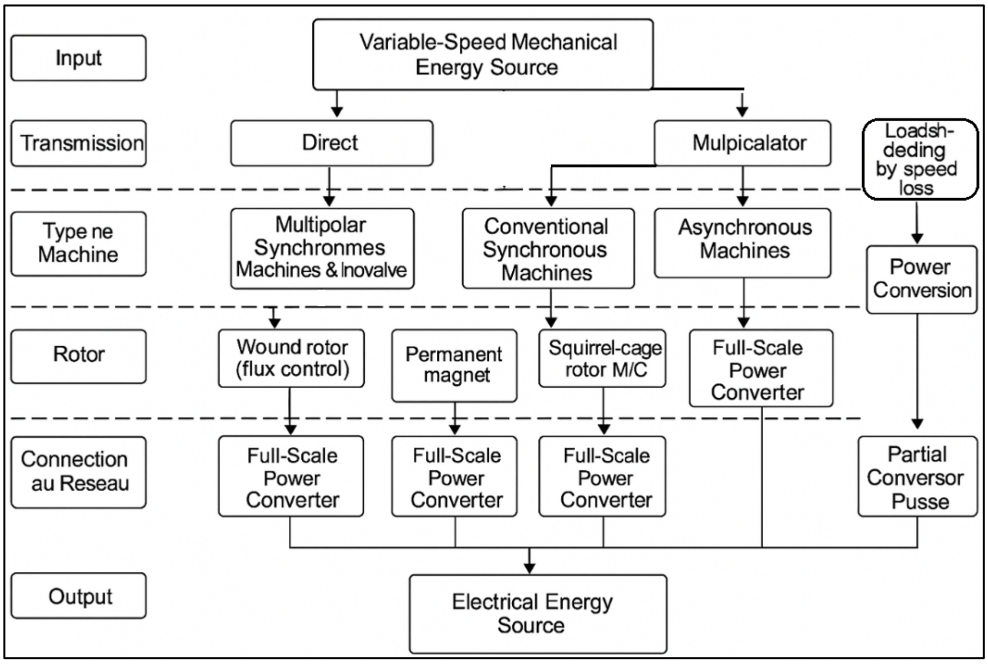


Figure 5-15: Process of converting mechanical energy into electrical energy for different electrical configurations.

5- Conclusion

Through the analysis of various wind-energy system topologies, it becomes evident that the choice of generator and converter configuration has a direct impact on efficiency, control flexibility, and overall system cost. Fixed-speed systems, though simple and robust, suffer from limited energy capture and poor adaptability to wind variations. In contrast, variable-speed systems especially those employing DFIG and PMSG technologies, offer superior performance, enabling maximum power tracking and reduced mechanical stress.

Ultimately, the integration of advanced power electronics allows modern wind-energy systems to deliver clean, stable, and controllable electrical power to the grid. The continuous improvement of these topologies reflects the growing importance of renewable energy in achieving sustainable development and reducing global dependence on fossil fuels.

Chapter 6: Problems and solutions

Problems

Problem 1:

I- Course question:

Choose the correct answer:

1- Which parameter directly influences the air density?

A) The height of the wind turbine mast

B) The humidity of the air

C) The temperature and pressure of the air

D) The wind speed

2- What is the fundamental factor that limits the amount of energy a wind turbine can extract from the wind?

A) The efficiency of the electrical generator

B) Betz's limit

C) The installation altitude

D) The roughness of the ground

3- If the wind speed increases from 10 m/s to 15 m/s, by how much is the recoverable power of the wind turbine multiplied?

A) 1.5

B) 2.25

C) 3.375

D) 4.5

II- Exercise:

A wind turbine with a diameter DDD operating at a given altitude is considered. The recoverable power of a wind turbine depends on atmospheric conditions, particularly the air density ρ\rhoρ, which varies with altitude and temperature according to the relation:

$$\rho = \frac{P}{R \times T}$$

Where:

P is the atmospheric pressure (Pa),

R=287 J/kg·K is the ideal gas constant for air,

T is the temperature in Kelvin (K).

Given:

Cp=0.42 (power coefficient of the wind turbine), Wind turbine diameter: $D=120$ m

Wind speed: $V=14$ m/s

Data:

- **Case 1:** Altitude = 0 m (sea level)
  - Pressure: $P=101325$ Pa
  - Temperature: $T=288$ K
- **Case 2:** Altitude = 1500 m (mountainous area)
  - Pressure: $P=85000$ Pa
  - Temperature: $T=278$ K

Questions:

- Calculate the air density ρ\rhoρ for both altitudes.
- Calculate the recoverable power of the wind turbine in both cases.
- Determine the impact of altitude on wind power in percentage (ΔP).
- Propose two technical solutions to compensate for this efficiency loss.
- What are the main factors influencing the efficiency of a wind turbine?

Problem 2:

A wind turbine with a diameter of 50 meters is installed in a region where the wind blows at an average speed of 12 m/s. The air density under these conditions is 1.225 kg/m^3.

The wind turbine has a power coefficient $Cp=0.4$ and no losses (all efficiencies are assumed to be equal to 1).

The wind turbine parameters are as follows:

- Gear ratio: $G=60$
- Rotational speed of the primary shaft: $Nt=18$ rpm

The wind turbine is connected to an electrical grid and supplies a station that continuously consumes 200 kW.

Questions:

- What are the different types of energy losses in a wind turbine, and how can they be minimized?
- Calculate the wind power available on the swept area of the wind turbine.
- Determine the mechanical power transmitted to the primary shaft.
- Can the station be continuously supplied by this wind turbine alone? Justify.

- Calculate the rotational speed of the generator in rpm.
- Determine the torque at the output of the primary shaft and the torque transmitted to the generator.
- Compare the power supplied by the wind turbine if the wind speed increases by 50% and deduce the impact of wind speed on electricity production.
- What should be the length of the blades of a wind turbine operating under the same parameters (wind speed of 12 m/s) to produce a mechanical power of 2 MW?
- What are the main factors influencing the efficiency of a wind turbine?

Problem 3:

A company wishes to evaluate the performance of a wind turbine installed in a windy region. However, some data is missing and must be determined from the following information:

- Available wind power: Pv=1,800,000 W
- Wind turbine power factor: Cp=0.30
- Gear ratio: G=50
- Nominal speed of the generator: Ng=750 rpm
- Torque transmitted to the generator: Cg=6,000 N.m
- Blade length: a=30 m
- Aerodynamic coefficients: C_{rot}=0.7, C_{axe}=0.1
- Average blade surface: A=4.8 m²
- Measured incidence angle: i=8°
- Wind speed: V=12 m/s
- Air density: ρ=1.225 kg/m³

Based on this data, answer the following questions:

- Determine the mechanical power transmitted to the generator.
- Calculate the nominal speed of the rotor.
- Find the torque at the output of the primary shaft of the wind turbine.
- Assuming the wind turbine complies with Betz's limit, determine the maximum recoverable power.

- Verify the type of wind turbine.
- Calculate the inclination angle of the blade β\betaβ.
- Calculate the different forces T, P, and F_{rot} (Drag, Lift, and Rotation).
- A shorter blade requires a higher β\betaβ. Is this statement true or false? Justify your answer.
- When the wind exceeds the nominal speed, the wind turbine adjusts β (pitch control technique). Why?
- Why do modern wind turbines generally use three blades?

Problem 4:

A company is installing a wind turbine in a region with high wind energy potential and wants to determine certain mechanical quantities related to its operation. You have the following data:

- Rotational force applied to the blades: F_{rot}=3500N
- Thrust coefficient: C_{rot}=0.78
- Axial coefficient: C_{axe}=0.12
- Average blade surface: A=5.5m²
- Angle of incidence: i=7°
- Wind speed: v=11m/s
- Blade length: a=22m
- Gear ratio: G=45
- Nominal speed of the generator: Ng=1050 rpm
- Air density: ρ=1.225 kg/m³

Questions:

1. Determine the tangential velocity of the blades Vt.
2. Why must the tangential velocity of the blades Vt be optimized to maximize the efficiency of the wind turbine?
3. Determine the wind power Pv.
4. Calculate the mechanical power transmitted to the generator P_{mec} if the turbine captures 42% of the wind energy.
5. Find the relative wind speed on the blades W.

6. Calculate the thrust force PPP applied to the blades.
7. Determine the traction force T.
8. Determine the type of wind turbine.
9. Calculate the blade inclination angle β.

Problem 5:

A wind turbine with a diameter of 108 m is subjected to a wind blowing at 14 m/s. The air density is 1.225 kg/m³. The recoverable power is given by the formula:

$$P = 0.15 \times D^2 \times V^3$$

It is considered that the theoretical efficiency limit of a wind turbine is given by Betz's limit, which sets the downstream wind speed at:

$$V_2 = \frac{1}{3} V_1$$

and the maximum recoverable power at:

$$\mathrm{P}_{max} = \frac{16}{27} P_{vent}$$

An older wind turbine, with a diameter of 32 m, has been replaced by the current model. The effect of doubling the wind speed is also to be studied.

Questions:

1. Determine the recoverable power PPP in megawatts (MW) for this wind turbine.
2. Calculate the mass of air passing through the wind turbine per second.
3. Determine by how much the recoverable power has been multiplied when upgrading from the old wind turbine (32 m) to the current model (108 m).
4. Calculate by how much the recoverable power is multiplied if the wind speed increases from 14 m/s to 28 m/s, for the same diameter.
5. Determine the expression for the diameter of the "air tube" at the exit Φs in terms of the initial diameter Φ and wind speed V1.
6. Calculate its value for Φ=108 m.
7. Show that the constant used in the power formula is consistent with theory, and deduce the power coefficient Cp of this wind turbine.
8. Demonstrate Betz's Limit (59.3%).

Correction of the Problems:

Correction of the Problem 1:

I- Course question:

Choose the correct answer(s):

1- Which parameter directly influences air density?

C) Temperature and air pressure.

2- What is the fundamental factor that limits the amount of energy a wind turbine can extract from the wind?

B) Betz's limit.

3- If the wind speed increases from 10 m/s to 15 m/s, by how much is the recoverable power of the wind turbine multiplied?

C) 3.375.

II- Exercise:

1. **Calculation of air density (ρ) at different altitudes**

The air density varies with altitude and temperature according to the ideal gas law:

Case 1: Altitude = 0 m (Sea level)

$\rho_1 = \frac{P}{R\times T} = \frac{101325}{287\times 288} = 1.225\ \mathrm{kg/m^3}$.

$\rho_1 = 1.225\ \mathrm{kg/m^3}$

Case 2: Altitude = 1500 m (Mountainous area)

$\rho_2 = \frac{P}{R\times T} = \frac{85000}{287\times 278} = 1.065\ \mathrm{kg/m^3}$.

$\rho_2 = 1.065\ \mathrm{kg/m^3}$.

2. **Calculation of the recoverable power of the wind turbine at both altitudes**

The recoverable power of a wind turbine is given by the formula:

$$P = \frac{1}{2}\,.\rho.Cp.S.v^3$$

The swept area is:

$S = \pi.R^2 = \frac{\pi}{4}D^2$

$S = \frac{\pi}{4}120^2$;

$S = 11304\ m^2$

Case 1:

$P_1 = \frac{1}{2}\,.\rho.Cp.S.v^3 = \frac{1}{2}\times 1.225 \times 0.42 \times 11304 \times 14^3$

$P_1 \approx 7.979\text{MW}$

Acceptable values:

$$P_1 \approx 7.93 \text{ à } 7.98 \text{ MW}$$

Case 2:

$P_2 = \frac{1}{2} .\rho.Cp.S.v^3 = \frac{1}{2} \times 1.065 \times 0.42 \times 11304 \times 14^3$

$P_2 \approx 6.937\text{MW}$

3. **Impact of altitude on power in percentage**

The power loss due to altitude is given by:

$P_1 \quad \rightarrow \quad 100\%$

$(P_1 - P_2) \rightarrow \quad \Delta p$

$\Delta P = \frac{(P_1 - P_2)}{P_1} \times 100$

$\Delta P = \frac{(7.979 - 6.937)}{7.979} \times 100$

$\Delta P = 13.05\%$.

➞ An altitude of 1500 m results in a **13.05% decrease** in the recoverable power of the wind turbine.

---

4. Two technical solutions to compensate for this efficiency loss

✓ 1. Increase the blade diameter

✓ 2. Select sites with stronger winds

✓ 3. Improve blade design

5. What are the main factors influencing the efficiency of a wind turbine?

- Power coefficient (C_p).
- Mechanical losses.
- Electrical losses
- Meteorological or environmental/climatic conditions

Correction of the Problem 2:

1- What are the different types of energy losses in a wind turbine, and how can they be minimized?

- **Aerodynamic losses:** Improve blade design.
- **Mechanical losses:** Use high-quality bearings and lightweight materials.
- **Electrical losses:** Use more efficient generators and inverters.

2- Calculation of wind power Pv

Wind power is given by the formula:

$P_v = \frac{1}{2}\rho S_0 v^3 = \frac{1}{2}\rho\pi R^2 v^3 = \frac{1}{2} \times 1.225 \times \pi \times 25^2 \times 12^3 = 2\ 077\ 110W$;

$P_v = 2\ 077\ 110W$

3- Calculation of the mechanical power transmitted to the primary shaft

$P_{mec} = Cp.P_v \quad P_{mec} = 0.45 \times 2\ 077\ 110W$;

$P_{mec} = 934\ 699{,}5W$

4- Verification of the station's power supply

The station consumes 200 kW. The wind turbine produces 934.7 kW, so:

$P_{électrique} > P_{station}$

✓ YES, the wind turbine can continuously supply the station.

5- Calculation of the rotational speed of the generator

$N_g = G \times Nt = 60 \times 18 = 1080 tr/min$

$N_g = 1000 tr/min$

6- Calculation of mechanical torques

The torque at the output of the primary shaft is given by the relation:

$\Omega_t = \frac{2\pi N_t}{60} = \frac{2\times3.14\times18}{60} = 1.884 rad/s$;

$\Omega_t = 1.884 rad/s$

$P_{mec} = C_t \times \Omega_t \Rightarrow C_t = \frac{P_{mec}}{\Omega_t} = \frac{934\ 699{,}5}{1.884} = 496\ 125 N.m$;

$C_t = 496\ 125 N.m$

The torque transmitted to the generator:

$C_g = \frac{C_t}{G} = \frac{496\ 125}{60} = 8\ 268{,}75 N.m$;

$C_g = 8\ 268{,}75 N.m$

7- Impact of a 50% increase in wind speed

If the wind speed increases by 50%, the new speed becomes:

v′=1.5×v=1.5×12=18 m/s ;

v' = 18 m/s

Since wind power is proportional to the cube of wind speed:

$P'_v = \frac{1}{2}\rho S_0 v'^3 = \frac{1}{2}\rho\pi R^2 v'^3 = \frac{1}{2} \times 1.225 \times \pi \times 25^2 \times 18^3 = 7\ 010\ 246{,}25 W$;

$P'_v = 7\ 010\ 246{,}25 W$

Applying Cp, the final electrical power becomes:

$P'_{mec} = Cp.P'_v \quad P'_{mec} = 0.45 \times 7\ 010\ 246{,}25 W$;

$P'_{mec} = 3\ 154\ 610{,}8125 W$

Power increase factor:

$f_p = \frac{P'_{mec}}{P_{mec}} = \frac{3\ 154\ 610{,}8125}{934\ 699{,}5} = 3{,}375$;

$f_p = 3.375$

8- Blade length of a wind turbine operating under the same parameters to produce a mechanical power of 2 MW

$P'_v = \frac{1}{2}\rho S_0 v'^3 = \frac{1}{2}\rho\pi R^2 v'^3$ et $P'_{mec} = Cp.P'_v$

$P'_{mec} = Cp.\frac{1}{2}\rho\pi R^2 v'^3 \Rightarrow R = \sqrt{\frac{P'_{mec}}{Cp.\frac{1}{2}\rho\pi v'^3}} \Rightarrow R = \sqrt{\frac{2000000}{0.45 \times 0.5 \times 1.225 \times \pi \times 12^3}} = 36{,}56 m$

$R = 36{,}56 m$

9- What are the main factors influencing the efficiency of a wind turbine?

- Power coefficient Cp.
- Mechanical losses.
- Electrical losses.
- Meteorological or environmental/climatic conditions.

Correction of the Problem 3:

Correction of the Wind Turbine Section:

1. Mechanical power transmitted to the generator:

$P_{mec} = C_p . P_v$; $P_{mec} = 0.30 \times 1800000 = 540000\text{W}$;

$P_{mec} = 540000W$

2. Nominal speed of the rotor:

$N_t = \frac{N_g}{G} = \frac{750}{50} = 15\ tr/min$; .

$N_t = 15\ tr/min$

3. Torque at the output of the primary shaft of the wind turbine:

$C_t = C_g \times G = 6000 \times 50 = 300000\ N.$;

$C_t = 300000\ N$

4. Maximum recoverable power with Betz's limit:

$P_{max} = \frac{16}{27} \times P_{vt} = \frac{16}{27} \times 1800000;$

$P_{max} = 1066667W$

5. Verification of the type of wind turbine:

Angular speed of the rotor:

$\Omega_t = \frac{2\pi \mathrm{N}_t}{60} = \frac{2 \times 3.14 \times 15}{60} = 1.57 rad/s$;

$\Omega_t = 1.57 rad/s$

$\lambda = \frac{\Omega_t \mathrm{R}_t}{v} = \frac{1.57 \times 30}{12} = 3.925$

$\lambda = 3.925$

$\lambda > 3$ the wind turbine is classified as fast

6. Calculation of the inclination angle of the blade β:

$V_t = \Omega_t \times a = 1.57 \times 30 = 47.1 m/s$;

$V_t = 47.1 m/s$

$tg(i + \beta 1) = \frac{Va}{Vt_1} = \frac{12}{47.1} = 0{,}25 \Rightarrow i + \beta 1 = 14{,}29° \Rightarrow \beta 1 = 14{,}29° - 8° = 6.29°$;

$\beta 1 = 6.29°$

7. The different forces T, P et F_{rot}:

Relative wind speed on the blade:

$W = \sqrt{{V_t}^2 + {V_a}^2} = \sqrt{47.1^2 + 12^2} \Rightarrow$

$W = 48{,}60 m/s$

Drag force **T**:

$T = C_{axe} . A . \frac{\rho W^2}{2} \Rightarrow T = 0.1 \times 4.8 \times \frac{1.225 \times 48{,}60^2}{2} \Rightarrow$

$T = 6\ 94{,}416\text{N}$

Lift force P:

$P = C_{rot} . A . \frac{\rho {W_3}^2}{2} \Rightarrow P = 0.7 \times 4.8 \times \frac{1.225 \times 48{,}60^2}{2} \Rightarrow$

$P = 4\ 860{,}91\text{N}$

Rotation force F_{rot} :

$F_{rot} = P . Sin(\beta + i) - T . Cos(\beta + i) \Rightarrow$

$F_{rot} = 4\ 860{,}91 \times Sin(14{,}29°) - 6\ 94{,}416 \times Cos(14{,}29°) \Rightarrow$

$F_{rot} = 526{,}88N$

8-A shorter blade requires a higher β\betaβ, this statement is true.

To maximize lift PPP and increase energy production.

9-When the wind exceeds the nominal speed, the wind turbine adjusts β (pitch control technique) to reduce lift and prevent generator overload.

10-Modern wind turbines generally use three blades for a balance between efficiency, stability, and noise.

Correction of the Problem 4:

1. Calculation of the tangential velocity of the blades Vt.

The tangential velocity of the blades is given by the relation:

$$V_t = \frac{2\pi \mathrm{a} \mathrm{N}_t}{60}$$

where:

- a=22m is the length of a blade.
- Nt is the nominal rotor speed.

Determination of the nominal rotor speed N_t:

$N_t = \frac{N_g}{G} = \frac{1050}{45} = 23.33\ tr/min$; .

$N_t = 23.33\ tr/min$

Replacing N_t in the formula for V_t:

$V_t = \frac{2\pi \mathrm{a} \mathrm{N}_t}{60} = \frac{2\pi\times 22\times 23.33}{60}$;

$V_t = 53.76\ \mathrm{m/s}$

2. Why must the tangential velocity of the blades V_t be optimized?

The tangential velocity V_t plays a crucial role in the efficiency of the wind turbine. Optimizing V_t ensures that:

- If V_t is too low, the blades do not rotate.
- If V_t is too high, drag T increases and efficiency decreases.
- The tangential velocity is directly related to the power coefficient Cp.

3. Determination of wind power Pv.

The wind power is given by:

$P_v = \frac{1}{2}\rho S_0 v^3 = \frac{1}{2}\rho\pi R^2 v^3 = \frac{1}{2}\times 1.225\times\pi\times 22^2\times 11^3 = 1239594\ W$;

$P_v = 1239594\ W$

4. Calculation of the mechanical power transmitted to the generator $\mathrm{P_{mec}} = \mathrm{C_p}.\mathrm{P_v}$;

$P_{mec} = 0.42\times 1239594\ = 520\ 629{,}48\mathrm{W}$;

$P_{mec} = 520\ 629{,}48W$

5. Find the relative wind speed on the blades W

$W = \sqrt{Vt^2 + Va^2} = \sqrt{53.76^2 + 11^2} \Rightarrow$

$W = 54.84m/s$

6. Calculation of the thrust force PPP applied to the blades

The thrust force is given by:

$P = C_{rot}.A.\frac{\rho W^2}{2} \Rightarrow P = 0.78 \times 5.5 \times \frac{1.225 \times 54.84^2}{2} \Rightarrow$

$P = 7\,903{,}35$N

7. Calculation of the traction force T

$T = C_{axe}\,.A.\frac{\rho W^2}{2} \Rightarrow T = 0.12 \times 5.5 \times \frac{1.225 \times 54.84^2}{2} \Rightarrow$

$T = 1\,215{,}90$N

8. Determination of the type of wind turbine

The specific speed coefficient is given by:

$\lambda = \frac{\Omega_t.\mathrm{a}}{v} = \frac{\mathrm{V}_t}{v} = \frac{53.76}{11} = 4.88 > 3$

$\lambda = 4.88$

Other method:

$\Omega_t = \frac{2\pi \mathrm{N}_t}{60} = \frac{2 \times 3.14 \times 23.33}{60} = 2.44 rad/s$;

$\Omega_t = 2.44 rad/s$

$\lambda = \frac{\Omega_t.\mathrm{a}}{v} = \frac{2.44 \times 22}{11} = 4.88$

$\lambda = 4.88$

Since λ>3, the wind turbine is a high-speed type.

9. Calculation of the blade inclination angle β

The inclination angle is obtained by:

$tg(i + \beta 1) = \frac{V}{V_t} = \frac{11}{53.76} = 0{,}204 \Rightarrow \; i + \beta 1 = 11{,}56° \Rightarrow \beta 1 = 11{,}56° - 7° = 4.56°$;

$\beta 1 = 4.56°$

Correction of the Problem 5:

1. Calculation of the recoverable power in MW

The given formula for recoverable power is:

$P = 0.15 \times D^2 \times V^3$

Where:

D=108 m (wind turbine diameter),

V=14m/s (wind speed),

k=0.15 (coefficient given in the formula).

$P = 0.15 \times D^2 \times V^3$; $P = 0.15 \times 108^2 \times 14^3$; $P = 4\,800\,902{,}4$ W

2. Mass of air passing through the wind turbine

The mass flow rate of air passing through the wind turbine is given by:

$$\frac{\Delta m}{\Delta t} = \rho \times S \times V$$

$$S = \pi . R^2 = \frac{\pi}{4} D^2$$

$S = \frac{\pi}{4} 108^2$ *;*

$S = 9156.24\ m^2$

$\frac{\Delta m}{\Delta t} = 1.225 \times 9156.24 \times 14 = 157\ 029{,}516 Kg/s$

$\frac{\Delta m}{\Delta t} = 157\ 029{,}516 Kg/s$

3. Effect of diameter on power

The recoverable power is proportional to the square of the diameter:

$\frac{P_2}{P_1} = \frac{\frac{1}{2}.\rho.Cp.S_2.v^3}{\frac{1}{2}.\rho.Cp.S_1.v^3} = \frac{S_2}{S_1} = \frac{\frac{\pi}{4}{D_2}^2}{\frac{\pi}{4}{D_1}^2} = \frac{{D_2}^2}{{D_1}^2} = \left(\frac{D_2}{D_1}\right)^2$; $\frac{P_2}{P_1} = \left(\frac{D_2}{D_1}\right)^2$

The power is multiplied by 11.39 when increasing the diameter from 32 m to 108 m.

4. Effect of wind speed on power

The recoverable power is proportional to the cube of the wind speed:

$\begin{cases} P_2 = \frac{1}{2}\ .\rho . Cp . S_1 . {v_2}^3 \\ P_1 = \frac{1}{2}\ .\rho . Cp . S_1 . {v_1}^3 \end{cases}$ Donc : $\frac{P_2}{P_1} = \frac{\frac{1}{2}.\rho.Cp.S_1.{v_2}^3}{\frac{1}{2}.\rho.Cp.S_1.{v_1}^3} = \frac{{v_1}^3}{{v_2}^3} = \left(\frac{v_2}{v_1}\right)^3$; $\frac{P_2}{P_1} = \left(\frac{v_2}{v_1}\right)^3$

Initial wind speed: V1=14 m/s

New wind speed: V2=28 m/s (double)

$\frac{P_2}{P_1} = \left(\frac{v_2}{v_1}\right)^3 = \left(\frac{28}{14}\right)^3 = 8$;

$\frac{P_2}{P_1} = 8$

The power is multiplied by **8** when the wind speed doubles.

5. Diameter of the air tube at the exit of the wind turbine

According to Betz's limit, the wind speed at the exit is reduced to:

$\mathrm{V}_2 = \frac{1}{3}\,\mathrm{V}_1$

The mass flow rate must remain constant:

$\frac{\Delta m}{\Delta t} = \rho.S_1.v_1 = \rho.S_2.v_2 \quad \Rightarrow \rho.S_1.v_1 = \rho.S_2.v_2 \Rightarrow S_1.v_1 = S_2.v_2 \Rightarrow S_2 = \frac{S_1.v_1}{v_2}$

$$\Rightarrow S_2 = 3\,S_1$$

$\Rightarrow \frac{\pi}{4}\Phi\mathrm{s}^2 = 3\,\frac{\pi}{4}\Phi^2$; $\Rightarrow \Phi\mathrm{s} = \sqrt{3\Phi^2} \Rightarrow \Phi\mathrm{s} = \sqrt{3}\Phi = \sqrt{3} \times 108 = 187.06\mathrm{m}$

$\Phi\mathrm{s} = 187.06\mathrm{m}$

6. Justification of the formula and calculation of Cp

The power contained in the wind is given by:

$$P = \frac{1}{2}\,.\rho.Cp.S.v^3$$

$$S = \pi.R^2 = \frac{\pi}{4}D^2$$

$P = \frac{1}{2}\,.\rho.Cp.S.v^3 = \frac{1}{2}\,.\rho.Cp.\frac{\pi}{4}D^2.v^3 = k.D^2.v^3$

$P = k.D^2.v^3$ Since: $P = 0.15 \times D^2 \times V^3$

Comparing with the given formula:

$k = 0.15$

Since ; $k = \frac{1}{2}\,.\rho.Cp.\frac{\pi}{4}$ we equate:

$k = \frac{1}{2}\,.\rho.Cp.\frac{\pi}{4}$

$\Rightarrow k = \frac{\rho.Cp.\pi}{8} \Rightarrow \quad Cp = \frac{8k}{\rho.\pi}$ Alors $Cp = \frac{8.k}{\rho.\pi} = Cp = \frac{8 \times 0.15}{1.225 \times \pi} = 0.31$;

$Cp = \mathbf{0.31}$

General Conclusion

In this comprehensive course material, we have explored the key aspects of Wind Energy Conversion Systems, focusing on wind characteristics, wind energy conversion systems, components of wind turbines, and various important models for turbine performance and power generation. This course material is specifically designed to cater to doctoral and master's students in the field of electrical engineering, particularly those specializing in renewable energy with a focus on wind power.

The course delves into wind characteristics, discussing the fundamental definitions, measurements, and units associated with wind speed and direction. Understanding the distribution of wind speed is crucial, and we explored the Weibull distribution, its parameters, and methods for determination. Moreover, the wind profile calculation and its variations with altitude were thoroughly analyzed.

Moving on to Wind Energy Conversion Systems (WECS), we examined their definitions, types, and components. Understanding the types of wind turbines, such as Horizontal Axis Wind Turbines (HAWT) and Vertical Axis Wind Turbines (VAWT), provided valuable insights into their advantages and disadvantages. Additionally, we delved into blade design, operation strategies, and the power and torque coefficients that govern the performance of wind turbines.

The conversion of wind kinetic energy into mechanical energy was explored in depth, highlighting important concepts like Betz's Law and the Tip-Speed Ratio. The power coefficient and torque coefficient were thoroughly discussed, giving a clear understanding of the performance of wind turbines.

Modeling played a crucial role in this course, with simulations and diagrams providing a practical perspective on the theoretical concepts. Simulink diagrams showcased the simulation of wind turbine behavior, allowing students to observe the output angular velocity for different blade pitch angles (Beta).

To sum up, this course material aims to equip students with the essential knowledge and models necessary for a comprehensive understanding of Wind Energy Conversion Systems. By offering a blend of theoretical principles, modeling, and practical insights, it paves the way for a deeper exploration and advancement in the field of renewable energy, particularly wind energy. With the rapid evolution of renewable energy technologies, this course material provides a solid foundation for those aspiring to contribute to a sustainable and greener future.

Appendix 1

Solution:

Example 1:

Class (m/s)		Frequency %	Class x Freq
0	1	2.75	1.375
1	2	7.8	11.7
2	3	11.64	29.1
3	4	13.79	48.265
4	5	14.2	63.9
5	6	13.15	72.325
6	7	11.14	72.41
7	8	8.7	65.25
8	9	6.34	53.89
9	10	4.3	40.85
10	11	2.73	28.665
11	12	1.62	18.63
12	13	0.91	11.375
13	14	0.48	6.48
14	15	0.24	3.48
15	16	0.11	1.705
16	17	0.05	0.825
17	18	0.02	0.35
18	19	0.01	0.185
19	20	0	0
Sum		99.98	530.76

Average Speed	**5.308661732**

So, The probability density function of velocity:

$$P(V) = 0.29\left(\frac{V}{6.5346}\right)^{0.896} exp\left(-\left(\frac{V}{6.5346}\right)^{1.896}\right)$$

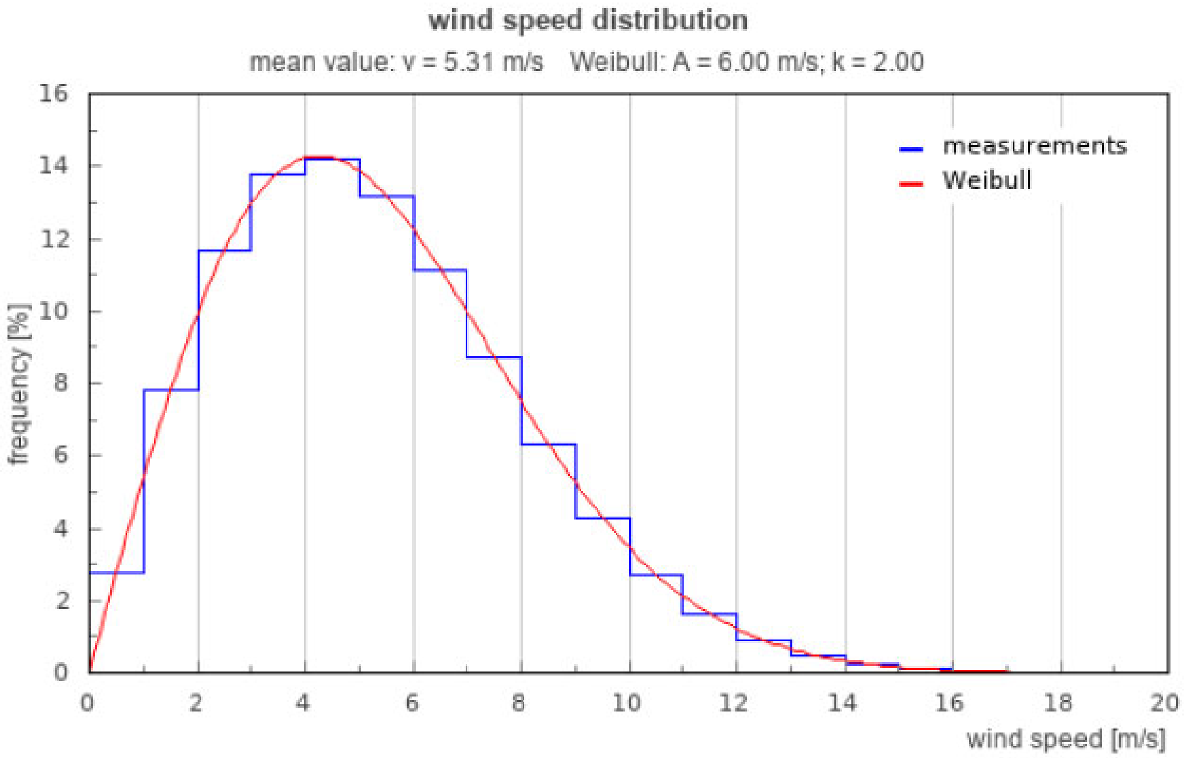


Fig Ax1. 1. Wind speed distribution

3. Wind Profile Calculation

Roughness Class	Roughness Length (z0)	Types of surfaces
0	0.0002m	Water, seas, lakes
0.5	0.0024m	Open terrain with bare surfaces (e.g., concrete, runways, mowed grass, etc.)
1	0.03m	Open agricultural terrain without fences, scattered constructions, and low-profile hills
1.5	0.055m	Agricultural terrain with a few buildings and hedges of 8 meters in height, spaced more than 1 kilometer apart
2	0.1m	Agricultural terrain with a few buildings and hedges of 8 meters in height, spaced approximately 500 meters apart
2.5	0.2m	Agricultural terrain with numerous buildings, bushes, and plants or hedges of 8 meters in height, spaced approximately 250 meters apart
3	0.4m	Villages, small towns, agricultural terrain with numerous hedges or tall trees, forests, very rugged terrain
3.5	0.6m	Large cities with tall buildings
4	1.6m	Large cities with tall buildings and skyscrapers

Appendix 2

Example 2:

Z0	0.01	Roughness length	
H1	10m	V1	5m/s

h	v
10	5
20	5.75257499
30	6.19280314
40	6.50514998
50	6.74742501
60	6.94537813
70	7.1127451
80	7.25772497
90	7.38560627
100	7.5
110	7.60348171
120	7.69795312
130	7.78485838
140	7.86532009
150	7.94022815

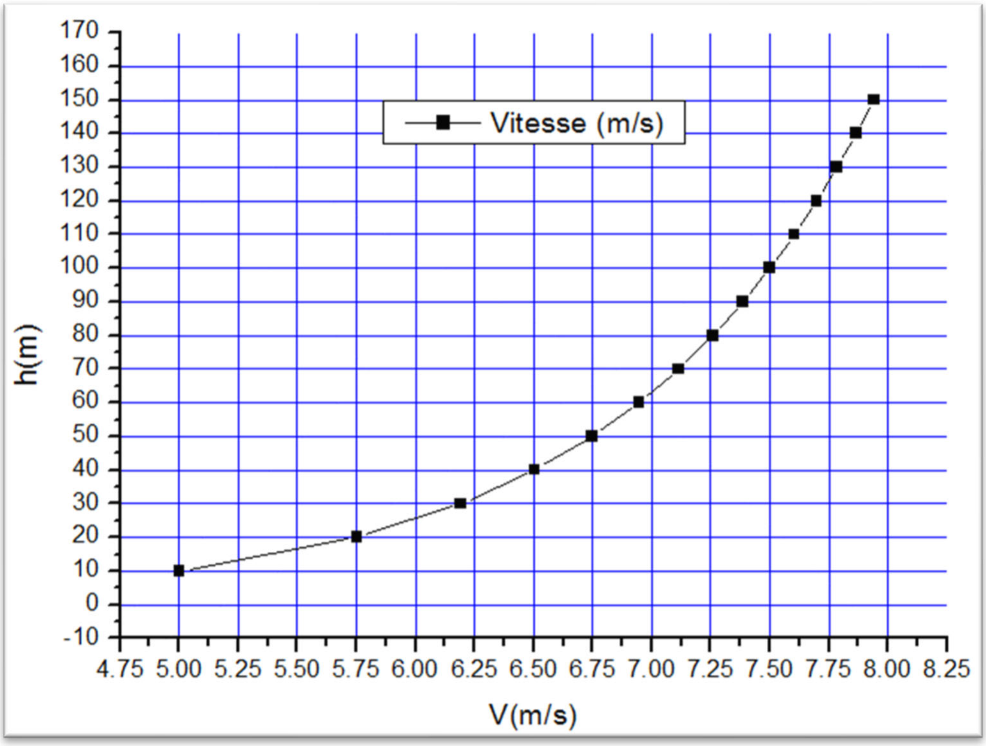


Fig Ax2. 1. Variation of wind speed with respect to height H

Appendix 3

Wind Turbine Simulation

Lab Objectives:

In this section, we complete the simulation of the wind turbine (Cp coefficient, turbine, gearbox, and shaft rotation speed) to calculate the turbine rotation speed, generator shaft rotation speed, and wind turbine shaft power for a given beta value and designated wind speed.

Simulink Diagram: (Part 1)

Run the simulation for 30s: Beta=6°, 10°, and V=10m/s

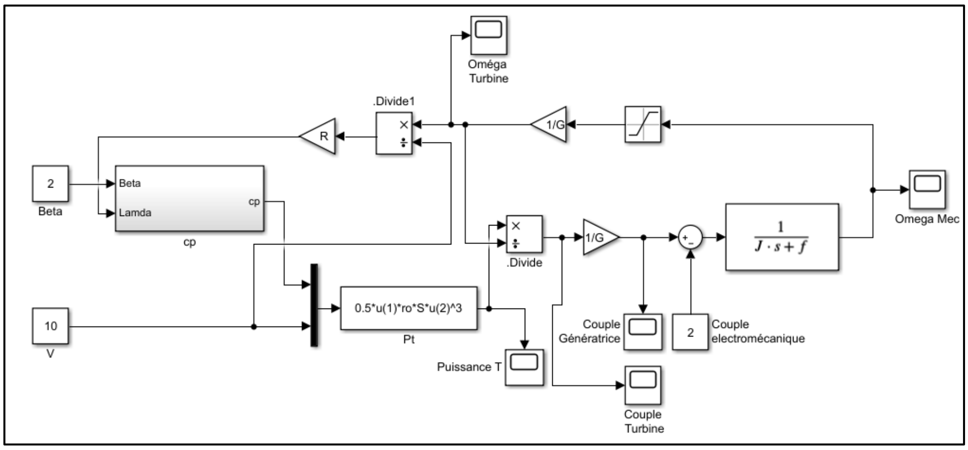
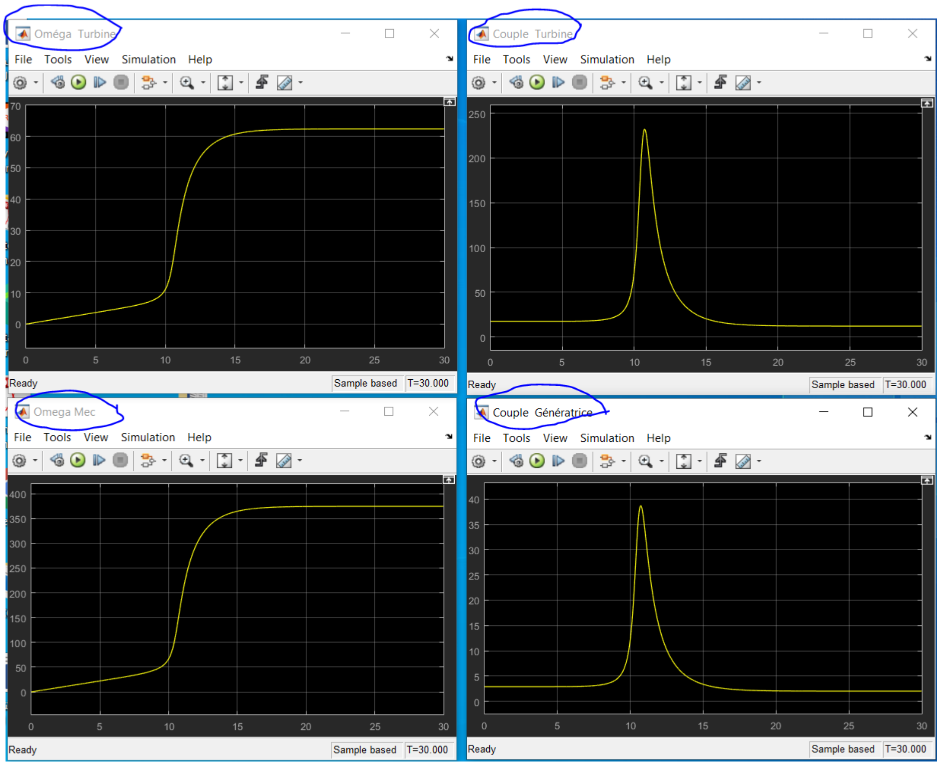


Fig Ax3. 1. Simulink Diagram (Part 1)

Results Graph: Paste the graphs for:

Beta=6°:



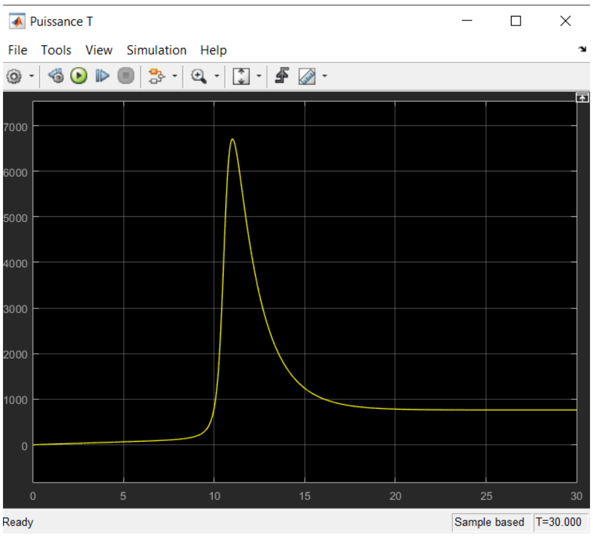
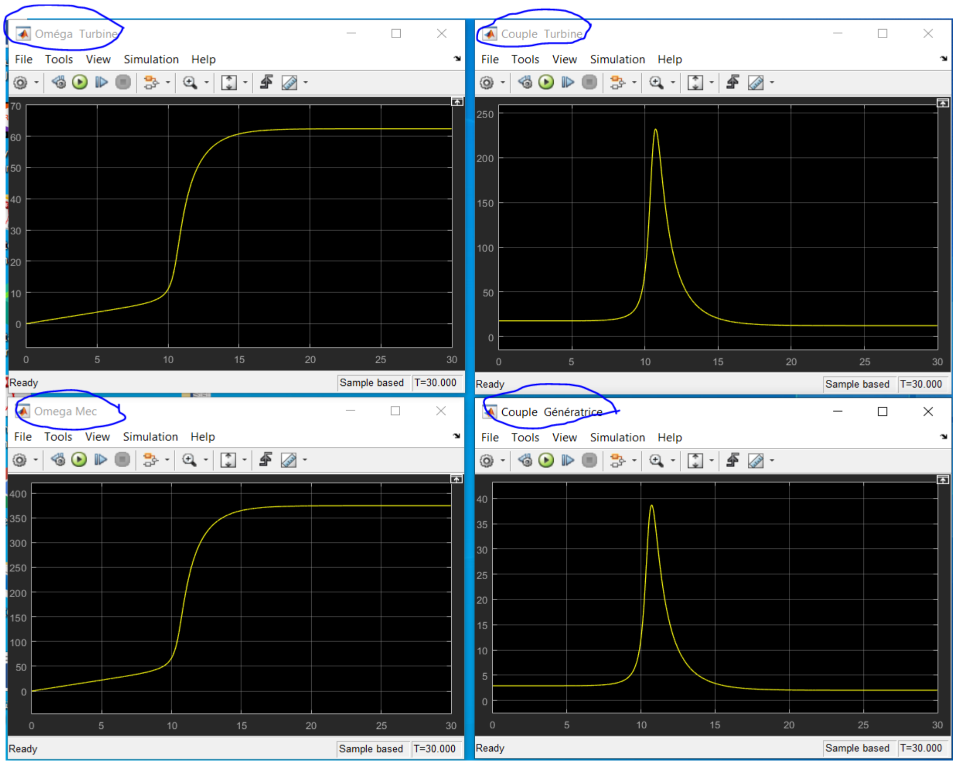


Fig Ax3. 2. Different results for Beta=6°:

Beta=10°:



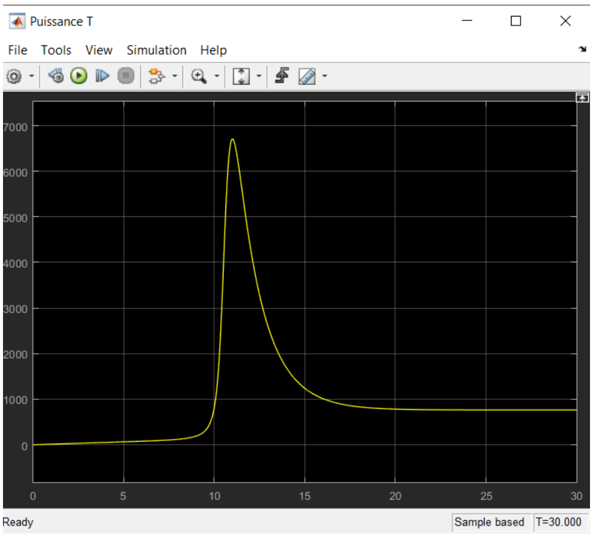


Fig Ax3. 3. Different results for Beta=10°:

Fill in the following table:

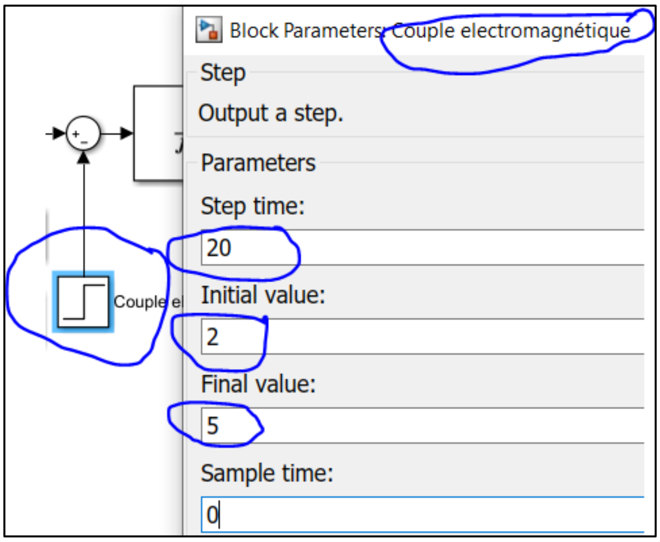
Beta	6°	10°
Mechanical Omega (shaft)	270 rd/s	270 rd/s
Turbine Omega	20 rd/s	20 rd/s
Generator Torque	30N.m	30N.m
Turbine Power	2000W	2000W

Simulink Diagram: (Part 2)

Run the simulation for 30s, Beta 6°:

For the speed in the 'V' block, use what is in Figure *Fig Ax3. 5*.

For the speed in the 'electromagnetic torque' block, use what is in Figure *Fig Ax3. 4*.



Block Parameters: Couple electromagnétique

Step

Output a step.

Parameters

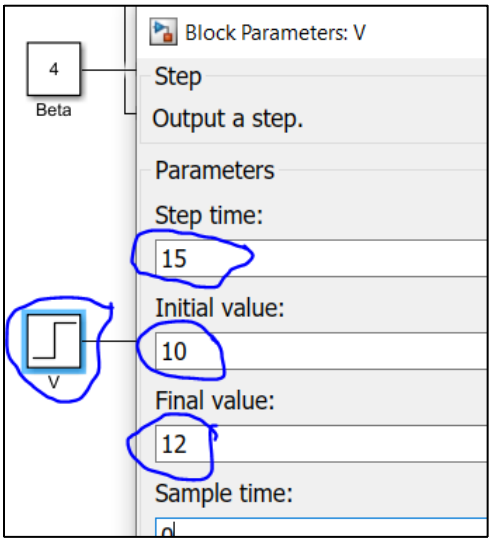
Step time: 20

Initial value: 2

Final value: 5

Sample time: 0

Fig Ax3. 4. Adjustment of the Electromagnetic Torque Step



Block Parameters: V

Step

Output a step.

Parameters

Step time:
15

Initial value:
10

Final value:
12

Sample time:
0

Fig Ax3. 5. Adjustment of wind speed Step

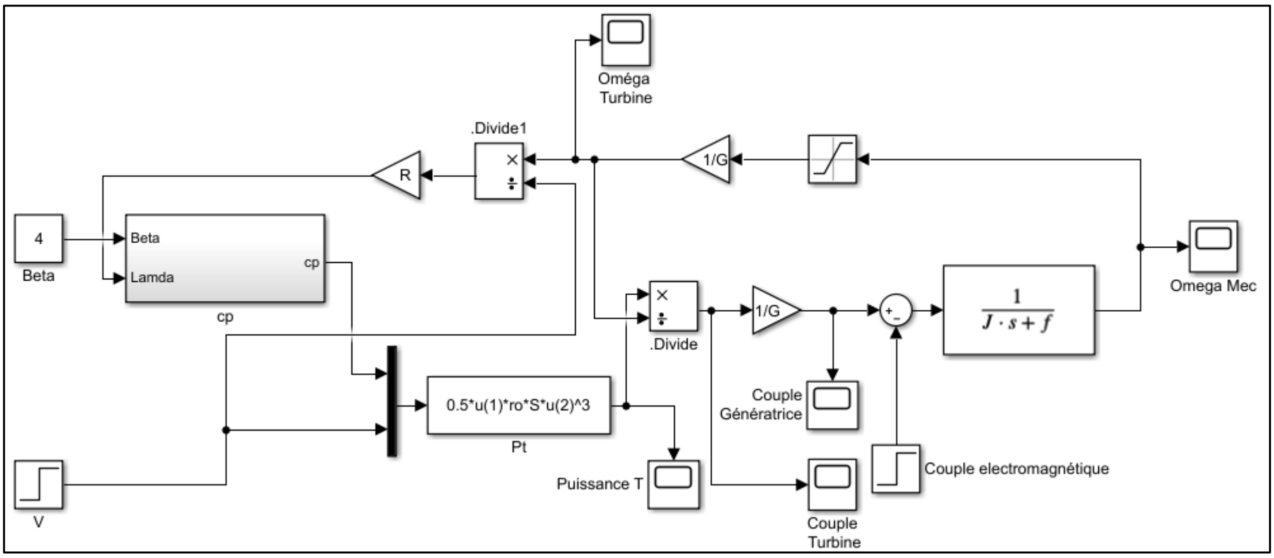


Fig Ax3. 6. Simulink Diagram (Part 2)

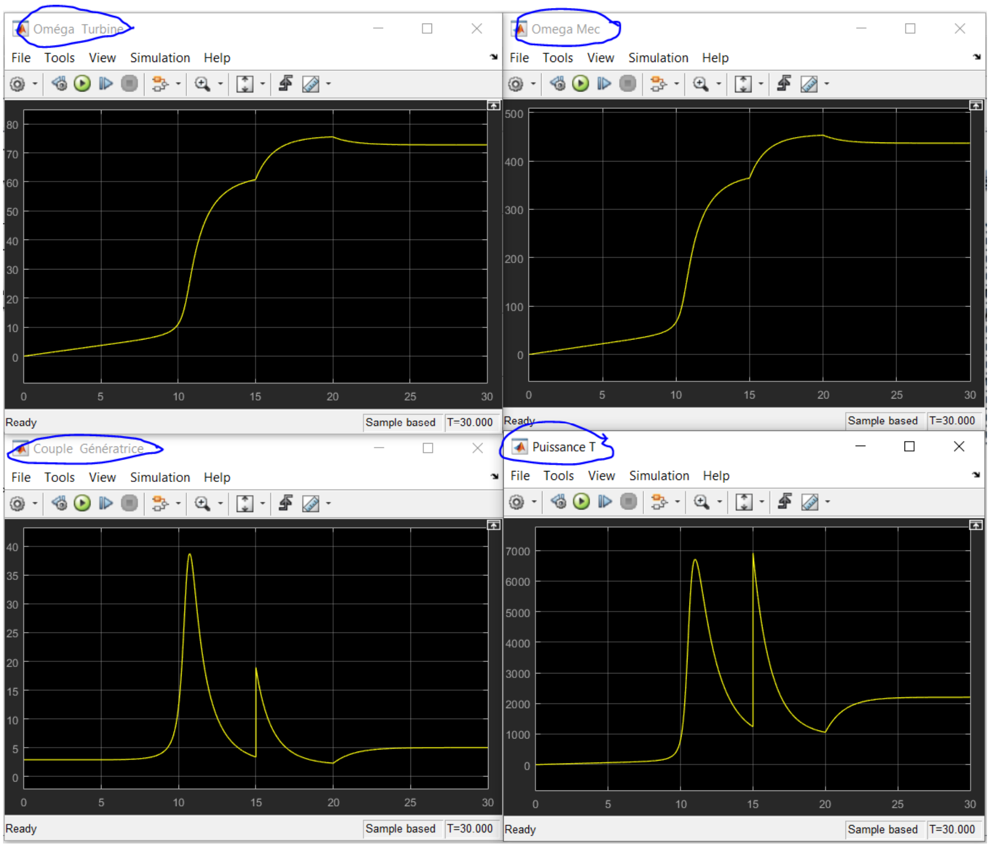


Fig Ax3. 7. Different results

Fill in the following table:

Beta	6°	6°	6°
Time	15s	20s	20s à 30s
Mechanical Omega (shaft)	70 rd/s	380rd/s	440 rd/s
Turbine Omega	10 rd/s	60rd/s	72 rd/s
Generator Torque	4N.m	2.5	4.8N.m
Turbine Power	500W	1200W	2200W

Drawing program for the three angles:

```
clc
om(:,1)=Omega2;
om(:,2)=Omega4;
om(:,3)=Omega6;
plot(t,om), grid
xlabel('t')
ylabel(' omega ')
legend('Beta=6°','Beta=4°','Beta=2°')
```

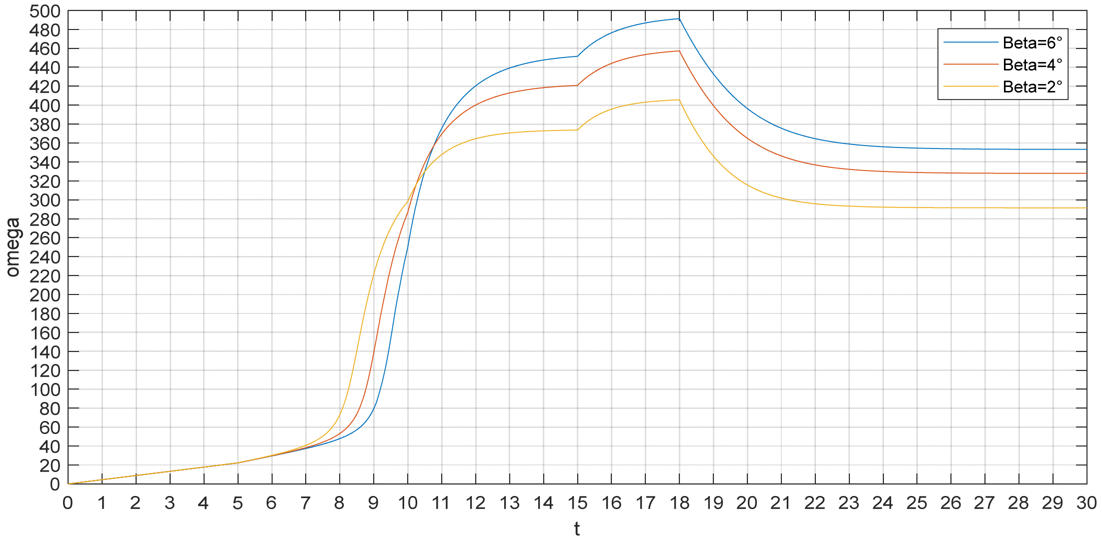


Fig Ax3.8. Omega Variation for 3 Angles

Appendix 4

Programme selon le Canvas ELT-Master_Energies_Renouvelables_Electrotechnique_MAJ 2022

Semestre 2
UE Fondamentale Code : UEF 1.2.1
Matière:Systèmes de conversion de l'énergie éolienne
VHS: 45h00 (Cours: 1h30, TD 1h30)
Crédits: 4
Coefficient: 2

Objectifs de l'enseignement :

Permettre aux étudiants d'acquérir des connaissances théoriques et pratiques approfondies sur éléments constitutifs des machines éoliennes de production d'électricité (aérogénérateurs).

Connaissances préalables recommandées :

Cours du M1 (UEF1 : Energies Renouvelables)

Contenu de la matière :

Chapitre 1Caractéristiques du vent

Météorologie du vent, distribution, variation de la vitesse du vent

Chapitre2Les systèmes de conversion éolienne (CCE)

Définition, principe de fonctionnement, types d'éoliennes (Autonomes, connectés aux réseaux), Architectures, la partie mécanique de la turbine

Chapitre 3 Conversion de l'énergie du vent

Transformation de l'énergie cinétique en énergie mécanique, coefficient de puissance, limite de Betz, vitesse spécifique (TSR), ...

Chapitre 4 Modélisation et simulation du système mécanique de l'éolien

Conversion électrodynamique, modèle de la turbine, caractéristique de puissance, techniques d'extraction de maximum de puissance avec et sans asservissement de la vitesse, limitation de puissance dans la zone de survitesse (Pitch contrôle).

Chapitre 5 Topologies des systèmes éoliens

État de l'art des systèmes éoliens, les différentes machines utilisées dans les systèmes de conversion éolienne (modélisation et simulation) : MAS, MSAP, MADA, GRV,…., les convertisseurs utilisés dans les systèmes de conversion éolienne (modélisation et simulation) : Convertisseur AC/DC, Convertisseur DC/AC, Convertisseurs DC/DC pour l'adaptation d'impédance, principe de raccordement de la chaine éolienne au réseau électrique.

Chapitre 6 Applications

Mode d'évaluation :

Contrôle continu : 40%, Examen : 60%.

Références :

- Multon et al., Aérogénérateurs électriques », Techniques de l'Ingénieur, Traités de Génie Electrique, 2004.
- **Rekioua, Djamila,** Wind Power Electric Systems: Modeling, Simulation and Control 2014 Series:Green Energy and Technology,EdSpringer, http://www.springer.com/energy/renewable+and+green+energy/book/978-1-4471-6424-1
- . Hau, Wind-Turbines, Springer, 2000.
- J.F. Manwell, J,G. McGowan and A,L. Rogers , Wind energy explained theory ,design and application, University of Massachusetts, Amherst, USA
- Gary L.Johnson, Wind energy systems, 2006
- Hills, R. L. (1994) Power from Wind. Cambridge UniversityPress, Cambridge, UK
- Nelson, V. (1996) Wind Energy and Wind Turbines. Alternative Energy Institute, Canyon, TX.
- Freris, L. L. (1990) Wind Energy Conversion Systems, Prentice Hall, London.

References

1- Abdelhafidh Moualdia, Polycopie de cours des aérogénérateurs, universite dr Yahya Fares de Medea.

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3- Manwell, J. F., McGowan, J. G., & Rogers, A. L. (2009). Wind Energy Explained: Theory, Design and Application (2nd ed.). Wiley.

4- Burton, T., Sharpe, D., Jenkins, N., & Bossanyi, E. (2011). Wind Energy Handbook (2nd ed.). Wiley.

5- Hansen, M. O. L. (2008). Aerodynamics of Wind Turbines (2nd ed.). Earthscan.

6- Gasch, R., & Twele, J. (Eds.). (2013). Wind Power Plants: Fundamentals, Design, Construction and Operation (2nd ed.). Solarpraxis AG.

7- Ochi, M. K. (2012). Power Generation, Operation, and Control. Academic Press.

8- Eldrén, J. (Ed.). (2015). Wind Power: Turbine Design, Selection, and Optimization. Springer.

9- Ce livre se concentre sur la conception des turbines éoliennes, la sélection et l'optimisation pour maximiser l'efficacité de la production d'énergie éolienne.

10- Archer, C. L., & Jacobson, M. Z. (2005). Evaluation of global wind power. Journal of Geophysical Research: Atmospheres, 110(D12).

11- Cet article offre une évaluation globale de la puissance éolienne, ce qui peut être utile pour comprendre le potentiel de l'énergie éolienne à l'échelle mondiale.

12- Eriksson, S., Bernhoff, H., & Leijon, M. (2008). Evaluation of different turbine concepts for wind power. Renewable and Sustainable Energy Reviews, 12(5), 1419-1434.

13- Cette revue propose une évaluation des différents concepts de turbines éoliennes, ce qui peut aider à choisir le type de turbine approprié pour un projet donné.

14- Hansen, A. M., Sørensen, P., & Madsen, H. A. (2005). Optimal control applied to wind turbines. Wind Energy, 8(3), 275-293.

15- Cet article se penche sur le contrôle optimal appliqué aux éoliennes, offrant ainsi des idées pour améliorer le rendement et l'efficacité des éoliennes.

16- Li, Y., Wu, W., Du, Z., & Wang, Y. (2014). Power smoothing control of wind power generation with energy storage system. IEEE Transactions on Sustainable Energy, 5(3), 954-962.