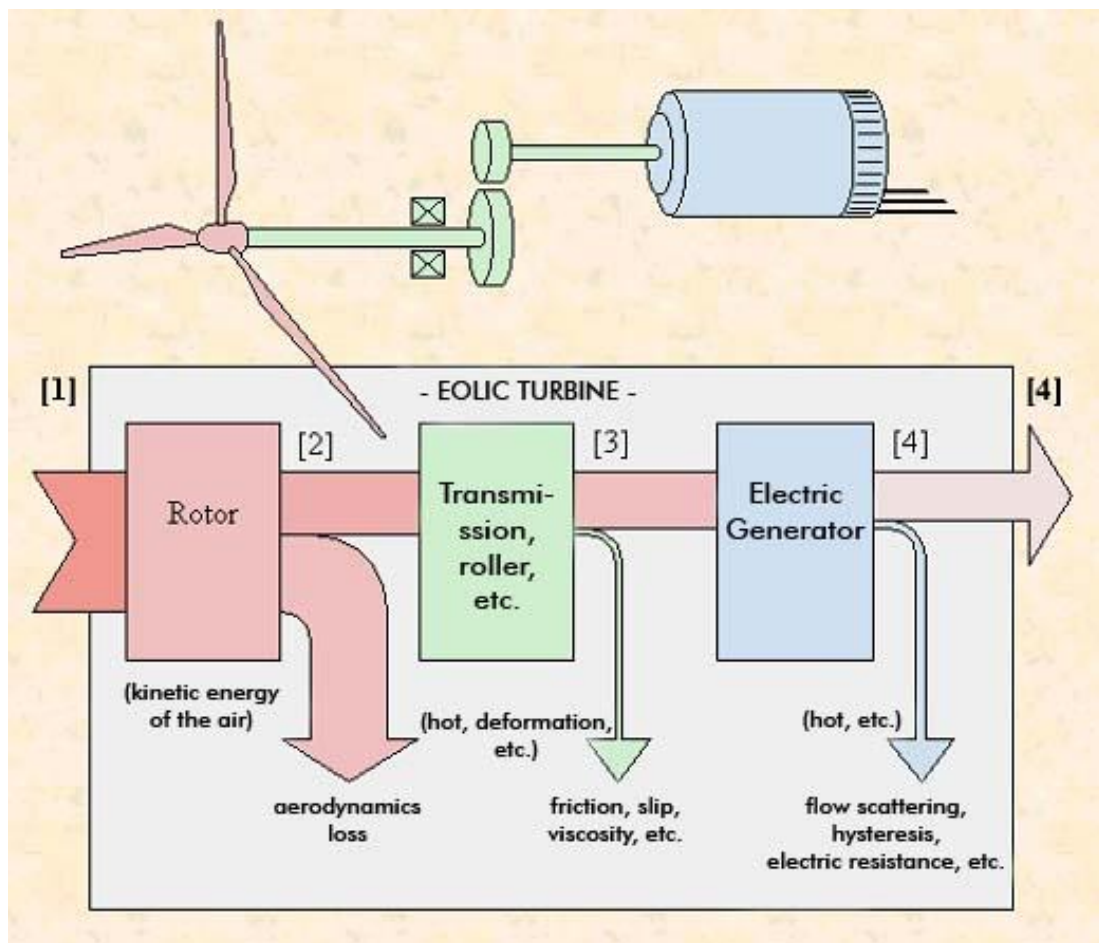# WIND ENERGY EXPERIMENTS

THEORETICAL BASICS

1.Main facts

An aerogenerator converts the wind force in a torque applied on the rotor blades. The proccess is briefly explained in the next image:

Transformation proccesses undergone by eolic energy in an eolic turbine can be understood as follows. The energy is first taken like kinetic energy from wind, (point 1 in the image), and it finally can be represented as a voltage or intensity value (point 4), going through different states.

The quantity of energy transferred from the wind to the rotor depends on the air density, the filtering area of the rotor and the wind speed.

The kinetic energy of a moving object is proportional to its mass, knowing that mass varies with density. Then, the kinetic energy of the air depends on its own density. So, the higher the density is, the higher the turbine energy is too, and therefore, the higher will be the generated power as well.

$$E_{kinetic} = \frac{1}{2} * M * V^2 \quad [Ec.\ 1]$$

On the other hand, air density changes with humidity and temperature. Both variables will be studied and their influence on the generated power will be determined.

The relation between temperature and density is inverse, so when temperature increases, density decreases.

To obtain density a psycometric chart can be used. It shows the properties of air and water mixtures at 1 atm of pressure. Temperature is represented in the X-axis and humidity in the Y-axis. The curve labelled with a "100%" represents the humidity of satured air. Lines which came from the saturation line are called adiabatic cooling. Knowing the temperature of the wet bulb and the dry bulb, which correspond to saturated and dry air temperatures respectively, air humidity can be determined as a percentage in Kg vapour/Kg of dry air. It is not only required to know the humidity, but density must be obtained as well. In the psicometric chart, saturated and dry air curves are represented versus air temperature, obtaining the specific volum in each case. By making an interpolation between these two specific values, the volume for these working temperature and humidity can be obtained.

Kinetic energy also depends on the speed. Wind energy changes with the average wind speed, as seen in the next figure:
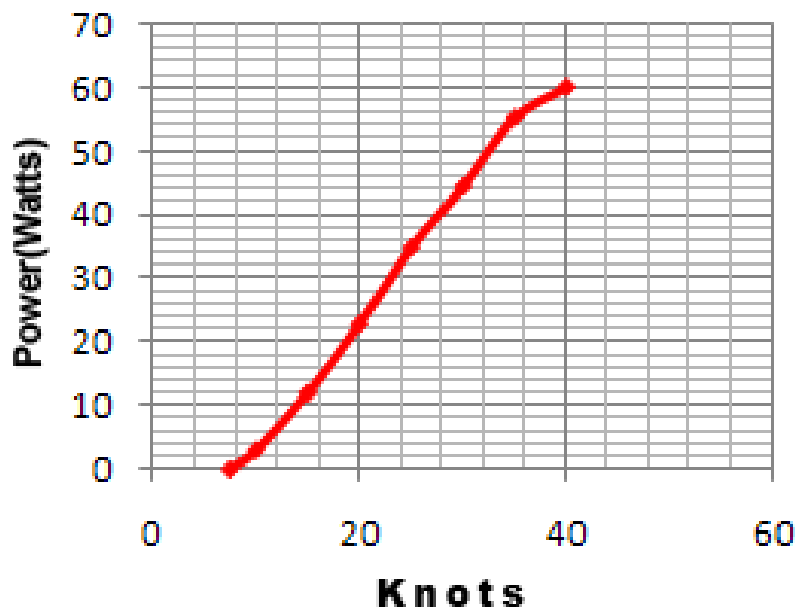
$$m/s = Knots*0.515$$

1.1. Wind deviation in the aerogenerator.

The turbine does not take the fully wind energy, it takes just a part. This is due to the fact that the aerogenerator changes the wind direction even before it reaches the rotor.

The rotor of the turbine restrains the wind when it takes some of its kinetic energy and trasforms it in rotational energy. So the speed of the wind in the outlet of the turbine is lower than in the inlet. The movement quantity equation says that the air flow in the inlet must be the same than in the outlet. Therefore, the outlet area must be greater than the inlet one, since speed decreases.

This difference among speeds creates a pressure gradient between the frontand the back parts of the rotor. In the front part, the pressure increases when the wind approaches the rotor, and it inmediately decreases after the rotor.

1.2 Ideal breaking of the wind.

The higher the amount of kinetic energy extracted from wind is, the slower the outlet speed will be. If kinetic energy is completely extracted, the speed in the outlet will be null, the air will not be able to get out of the turbine and no energy will be obtained. The other case would be if the air pass through the turbine with no speed change: in this case, no energy would be obtained.

In an ideal aerogenerator, the outlet speed will decrease until 2/3 of the inlet speed. In order to demonstrate this, a fundamental aerodynamics law is used (Betz Law).

1.3 The wind energy.
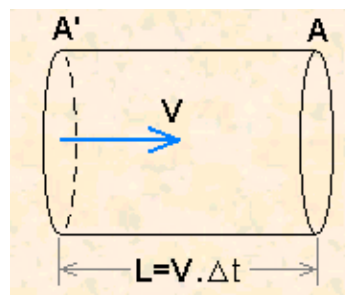
We have an straight section "A" tube, with this section fixed into the space. An "V" speed fluid passes through this tube with a mobile section A1, parallel to the A section. This A1 section moves with the fluid with a speed V, of constant module and direction perpendicular to its own section.

The length travelled by A' will be:

$$L = V * \Delta t \quad [\text{Ec. 2}].$$

The fluid contained in the volume over the tube defined by this length, L, has a mass of:

$$M = \rho * A * V * \Delta t \qquad [\text{Ec. 3}]$$

Where:

ρ air density;

V wind speed in the rotor;

A rotor area.

The kinetic energy that corresponds to this mass will be:

$$E_{kinetic} = \frac{1}{2} * \rho * A * V * \Delta t * V^2 \qquad [\text{Ec. 4}]$$

This energy divided by the time spent in travelling along the tube give us the wind energy:

$$P_{wind} = \frac{1}{2} * \rho * A * V^3 \quad [\text{Ec. 5}]$$

The power coefficient C_p is given by the relation between the energy captured by the rotor and the total wind energy. Then, the captured energy will be:

$$P_{captured} = C_p * \frac{1}{2} * \rho * A * V^3 \quad [\text{Ec. 6}]$$

However, along the process some mechanic and electric factors take place to define the total captured energy in the turbine. Mechanical efficiency of the rotor axis transmission and the electrical efficiency of the electrical generator are:

$$P_{captured} = \eta_{mec} * \eta_{elec} * C_p * \frac{1}{2} * \rho * A * V^3 \qquad [Ec. 7]$$

1.4 Betz Law.

Betz Law says that less than 59% of the kinetic energy of the wind can be converted into mechanical energy when using an aerogenerator.

Demonstration:

In order to demonstrate Betz Law we will start from the Rankine-Froude hypothesis:

1- The air is suppossed to be an ideal fluid with no fluid in the whole field, but near the rotor.

2- Movement in all the fluid field is subsonic, with a very low Mach numbers, so it can be considered no compressible. The thermic fluid problem is disacoupled of the mechanic one.

3- The movement of the fluid is stationary, that it is to say, it does not depend on time.

4- It is not taken into account the rotation of the rotor nor that of its trail.

5- The rotor is seen like a porous disc, composed by an infinite number of very thin plates.

Under these tight restrictions, the physical model used to describe it is shown in the next figure:
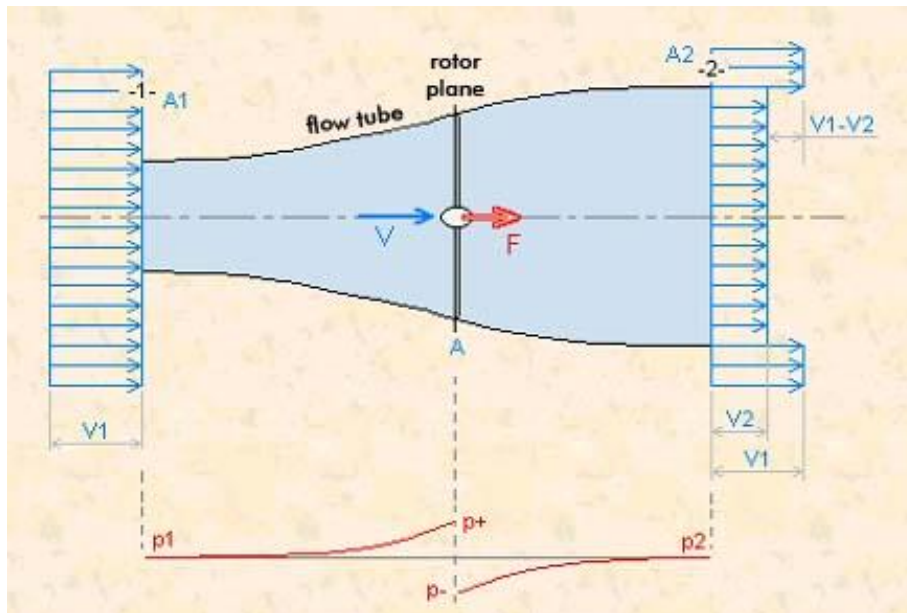
Applying the movement quantity equation:

$$M_1 * V_1 = M_2 * V_2 \qquad [\text{Ec. } 8]$$

$$M = \rho * A * V * \Delta t \qquad [\text{Ec. } 3]$$

Taking into account the hypothesis 3 (Δt = cte), the force applied on the rotor is:

$$F = \rho * A * V * (V_1 - V_2) \qquad [\text{Ec. } 9]$$

V_1 is the inlet speed;

V_2 is the outlet speed;

V is the rotor speed;

A is the rotor area.

The force applied on the rotor can be also computed from the pressure gradient created between the front and back sides of the rotor.

$$F = A*(p^+ - p^-) \qquad [\text{Ec. 10}]$$

p^+ is the pressure on the front side of the rotor;

p^- is the pressure on the back side of the rotor.

Applying the movement quantity equation between the inlet and the front of the rotor, and then between its back side and the outlet:

$$p_1 + \frac{1}{2}*\rho*V_1^2 = p^+ + \frac{1}{2}*\rho*V^2 \qquad [\text{Ec. 11}]$$

$$p_2 + \frac{1}{2}*\rho*V_2^2 = p^- + \frac{1}{2}*\rho*V^2 \qquad [\text{Ec. 12}]$$

p_1 is the inlet pressure.

p_2 is the outlet pressure.

As $p_1 = p_2$, equations 11 and 12 will be:

$$p^+ - p^- = \frac{1}{2}*\rho*(V_1^2 - V_2^2) \qquad [\text{Ec. 13}]$$

Substituting the previous equation in the Ec.10 and 9 are done in the same way:

$$V = \frac{(V_1 + V_2)}{2} \qquad [\text{Ec. 14}]$$

We define the parameter $K = \frac{V_2}{V_1}$ [Ec. 15]

Energy captured from the rotor:

$$P_{captured} = = F * \frac{dl}{dt} = F*V = \rho * A * V * (V_1 - V_2)*V =$$

$$\left(\rho * A * \frac{V_1+V_2}{2}\right)*\left(\frac{V_1^2}{2}-\frac{V_2^2}{2}\right)= \frac{1}{4}\rho * A * V_1^3 *(1+K)*(1-K^2) \quad \text{[Ec. 16]}$$

For a constant value of V_1, the energy is maximized with reference to K and a value of $K = \frac{1}{3}$ or $K=-1$ is obtained. The K value to be used will be $K = \frac{1}{3}$, as the negative value has no physical sense (both velocities have the same direction).

The maximum value of the energy cofficient is computed as follows:

$$C_{pmax} = \frac{P_{captadamax}}{P_{disponible}} = \frac{\frac{8}{27}*\rho*A*V_1^3}{\frac{1}{2}*\rho*A*V_1^3} = 0.5926 \quad \text{[Ec. 17]}$$

The energy extracted from the wind results in:

$$P_{extrated} = C_p * P_{wind} \quad \text{[Ec. 18]}$$

2. Wind statistics.

As wind speed is a random phenomenom, it is considered in an statistic way. When studying the wind with energetic purposes, it is interesting to know the speed frequency along the time, that is to say, for how long the wind has a given speed.

Average speed can be defined as follows: $\overline{V} = \dfrac{1}{n}\sum\limits_{i=1}^{n}V_i$ [Ec. 19]

where V_i are the registered speeds and n is the number of measured values. There are two statistical adjusted functions in order to describe this speed frequency along the time. One of them is that of Rayleigh and the other one is the Weibull function.

Following the Rayleigh distribution:

$$k = \dfrac{\pi}{4}*\left(\dfrac{V}{\overline{V}}\right)^2 \quad \text{[Ec. 20];} \quad R(V) = \dfrac{\pi}{2}*\dfrac{V}{\overline{V}^2}*e^{-k} \quad \text{[Ec. 21]}$$

where: V is the instantaneous speed of wind

$\overline{V}$ is the average wind speed in a place

Velocity distribution by Rayleigh
(V med = 6 m/s)
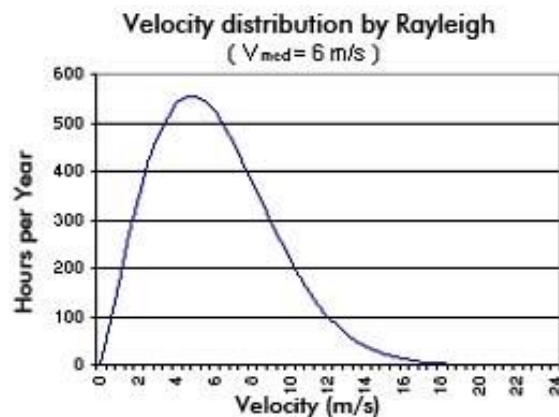
The following equation is considered: $P_{wind} = \frac{1}{2}*\rho*A*V^3$, so $P_{wind}/A = \frac{1}{2}*\rho*V^3$ is the energy per area unit. Then, the energy per area unit given by some wind with a V_i speed for a t_i time is:

$$E_i = \frac{1}{2}*\rho*V_i^3*t_i \qquad [Ec. 22]$$

Rayleigh function is not used for low speed values, lower than 4.5 m/s and it is strongly recommended not to use it under 3.6 m/s. Anyway, in low power regions it is not recommended to use a energy system like this, since this model give us enough information in the region of interest.

The Weibull function is:

$$W(V) = \frac{k}{c}*\left(\frac{V}{c}\right)^{k-1}*e^{-\left(\frac{V}{c}\right)^{\frac{1}{2}}} \qquad [Ec. 23]$$

Where c and k are shape and scale parameters respectively. This distribution has a higher precision than before, although that caracteristic parameters values, c and k, depend strongly on V_i and σ_i values measured in each particular case, that is to say, in a particular place.

The solution to these problems only has the purpose of setting up some relations between the instantaneous velocities and annual mean velocities, in order to evaluate the energetic efficiency of the turbine when placing it in a determined site, with a known annual mean velocity.

So, it is necessary to understand well the difference between the $\overline{V^3}$ and $\overline{V}^3$ ($\overline{V^3} > \overline{V}^3$) which let us to know that the available real power is higher than that computed from the average velocity.

The annual energy per area unit: $= \frac{1}{2} * \rho * \sum_{i=1}^{i=i\,max}\left(V_i^3 * t_i\right)$ [Ec. 24]

And as the time, following Rayleigh, in which the wind is defined by V_i and $V_i + \Delta V$ is: $t_i = R(V_i) * \Delta V * 8760$ [Ec. 25]

Total annual energy: $E = \frac{1}{2} * \rho * 8760 * \sum_{i=1}^{i=i\,max}\left(V_i^3 * R(V_i) * \Delta V\right)$ [Ec. 26]

On the other hand, the annual energy per area unit obtained from the annual mean velocity is: $\overline{E} = \frac{1}{2} * \rho * 8760 * \overline{V}^3$ [Ec. 27]

When relating 26 and 27 and considering Rayleigh equation:

$$\frac{E}{\overline{E}} = \frac{\pi}{2} * \sum_{i=1}^{i=i\,max}\left(\frac{V_i^4}{\overline{V}^5} * e^{\frac{\pi}{4}\left(\frac{V_i}{\overline{V}}\right)^2} * \Delta V\right)$$ [Ec. 28]

Solving the equation before we obtain that for any value of mean velocity we have: $\frac{E}{\overline{E}} = 1.91$ [Ec. 29]

$$E = 1.91 * \overline{E} = \frac{1}{2} * \rho * 1.91 * \overline{V}^3$$ [Ec. 30]

This shows that the total energy of a particular place can be estimed considering the speed as the mean speed multiplied by a factor given:

$$\overline{V^3} = 1.91 * \overline{V}^3$$ [Ec. 31]

And the mean annual power (8760 hours) for this place:

$$\overline{P} = \frac{1}{2} * \rho * A * \left(1.91 * \overline{V}^3\right)$$ [Ec. 32]

3. Optimum number of blades.

The eolic turbines can have different number of blades in its rotor. The more frequent is to find one, two, three or four blades rotors, although our rotor (with didatic purpose) has six blades. The main rule is that as lower number of blades we obtain a higher speed rotation in its axis. The magnittude which gives information about this topic is the specific speed, λ, which is obtained when dividing the tangential velocity of the point of the blade and the wind speed:

$$\lambda = w * R \, / \, v_{wind} \qquad [\text{Ec. 33}]$$

where:

ω is the rotation speed of the rotor in rad/s;

R is the radius of the rotor.
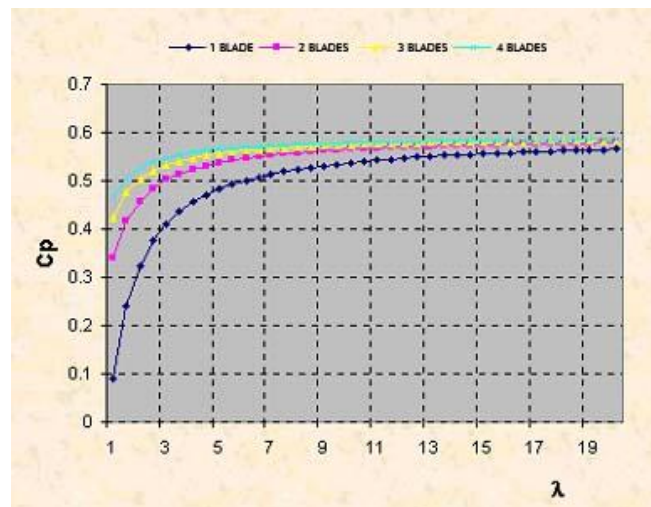
In practice, the number of blades is a funcion of the specific speed which can be expressed as:

$$\lambda_0 = \frac{\omega * R}{V} = \frac{\pi * D * N}{60 * V} \qquad [\text{Ec. 34}]$$

N rotation speed in rpm;

V wind speed in m/s;

D is the diameter of the rotor.

Specific speed	Number of blades
1	From 8 to 24
2	From 6 to 12
3	From 3 to 6
4	From 2 to 4
5 or more	From 2 to 3

Considering the previous options, we can assure that the cases where there are more than four blades correspond to slow eolics and the four or less blades cases correspond to fast eolics.

Due to the function of the number of blades, a decreasing in efficiency appears as result of an energy lost related to an increasing of turbulences. So this efficiency decreasing can be expressed as follows:

$$\eta_p = \left(1 - \frac{0.93}{p\sqrt{\lambda_0^2 + 0.445}}\right)^2 \qquad \text{[Ec. 35]}$$

p number of blades;

λ_0 specific speed.

In the design of eolic turbines for generating electricity it is recommended that the rotation speed of the rotor is as high as possible because this will produce a decreasing in size and weight of the electric generator and the multiplier system. Alos, it can be make cheaper the system, because the prize of the blades reachesa 20% of the total value of the unit. On the other hand, the aerodynamic efficiency increases when the number of blades increases too, but it is not important in the more than 3 blades cases. Another important aspect, from the point of view of the kinetic energy, is the decreasing of the mass of the blades.

4. Rotor diameter

The objective is to obtain the nominal power for the situation in which the wind speed is lower than the nominal one.

The maximum energy in an eolic energy converter is given by the next expression:

$$P_{total} = \eta_{mec} * \eta_{elec} * C_p * \frac{1}{2} * \rho * A * V^3 = \eta_{mec} * \eta_{elec} * C_p * \frac{1}{2} * \rho * \frac{\pi * D^2}{4} * V^3 \; [\text{Ec. 36}]$$

Suppossing the efficiency and density as constant, then, the power only depends on the speed and the diameter. Knowing the power we want to obtain and the working speed, when isolating from the previous equation we obtain:

$$D = \sqrt{\frac{8 * P_{total}}{\eta_{mec} * \eta_{elec} * C_p * \rho * \pi * V^3}} \quad [\text{Ec. 37}]$$

However, we have to take into account that the diameter of the rotor should be as low as possible in order to make the system cheaper, but obtaining the highest efficiency possible.

We have also to keep in mind that a value lower than 0.35 for the power coefficient represents a bad efficiency of the turbine, which works under its maximum possibilities. As the speed is the main factor, in ordert to obtain the diameter of the turbine it is necessary to know the average speed of the place to assure a good efficiency of the system.

5. Rotational speed of the rotor

For this kind of systems it is desired to get the greatest number of revolutions in the rotor, in order to reduce the size of the electric generator and the multiplier. Also, from the point of view of the rotor maximum rotational speed should be compatible with the structural resistance of the blades.

The maximum speed supported by a turbine is 60 m/s, whis is considered as a survival speed..

6. Height of the rotor axis

In order to obtain the height of the aerogenerator it is important to know the relation between the speed on the earth surface and the wind speed in any other point.

The increasing of the wind speed when getting far from the surface is a well known phenomenom. This change in wind speed depends on the point in which we measure. The turbulence of the air in the athmosphere and the air friction against the surface determine the form of this variation.

In the athmosphere, two kinds of turbulences can be defined: from a mechanical origin or from a thermal origin. The first one is produced when the air finds some obstacle on the surface. These obstacles produce some turbulences of a size that depends on the average wind speed and the size and shape of the obstacles. Thermal turbulence is produced due to the hot air going up and cold air going down. Both kinds of turbulences are simultaneously produced and the predominance of one over the other will define the aerodynamical state. Thermal turbulence can be of three types: non-stable, neutral and stable. In the non-stable case, temperature decreases with the height and the obstacle-turbulence is amplified and carried on. Under a neutral atmosphere, temperature is nearly constant with the height, so none air flow change produces any modification. The stable case appears when temperature increases with height and its effect on perturbations is strongly shock absorber.

When the speed of the wind increases, the influence of the difference between surface and air temperatures decreases and conditions are close to a neutral stability.

There are some theories to explain this phenomenom in a mathematical way. Application of these theories are divided in short periods (instant velocities) and long periods (average velocities).

If the height rotor axis election is treated from the point of view of the power capture, it is interesting to apply the theories for long periods. These theories are based on a distribution of one or a group of turbines in a place with a known velocities distribution against time (Weibull´s probability series). Some authors give the next equation:

$$\frac{\overline{V}(Z)}{\overline{V}(Z_{REF})} = \left(\frac{Z}{Z_{REF}}\right)^{\alpha} \quad \text{[Ec. 42]}$$

Where $\overline{V}(Z_{REF})$ is the mean speed in Z_{REF} (reference height) and α is a coefficient which depends on the roughness and the atmospheric stability of the considered place.

We can obtain α (for Z_0 between 0.05 and 0.5) if following the next equations:

$$\alpha = \frac{0.37 - 0.088 * Ln(\overline{V}(Z_{REF}))}{1 - 0.088 * Ln(Z_{REF}/10)} \quad \text{[Ec. 43]}$$

The second point of view, called Potential Law, takes $\alpha = 1/7$ and it can only be applied in low roughness places.

As the energy to be captured is proportional to the cube of the speed, the available energy at Z metres and Z_{REF} metres over the surface is given by:

$$\frac{E}{E_{REF}} = \frac{Z}{Z_{REF}} \quad \text{[Ec. 44]}$$

From this expression we can conclude that, in order to take the greatest quantity of power, we should place the turbine axis as far from the surface as possible, because when the height increases, the captured energy increases too.

Nevertheless, the choice of the rotor axis height finds some limitations. First of all, we have structural limitations. A too tall tower must be strong enough to support the great stresses produced by the wind on its blades, both static and dynamic stresses. Besides, all dynamic stresses on the rotor components are greater than in a smaller tower.

Another point of view is the economic one. A tower of really great dimensions which supports high stresses obviously requires the use of higher quality materials, more complex structures, etc. All these considerations cause the system to be more expensive, which make us evaluate this money rise related to the captured power increase.
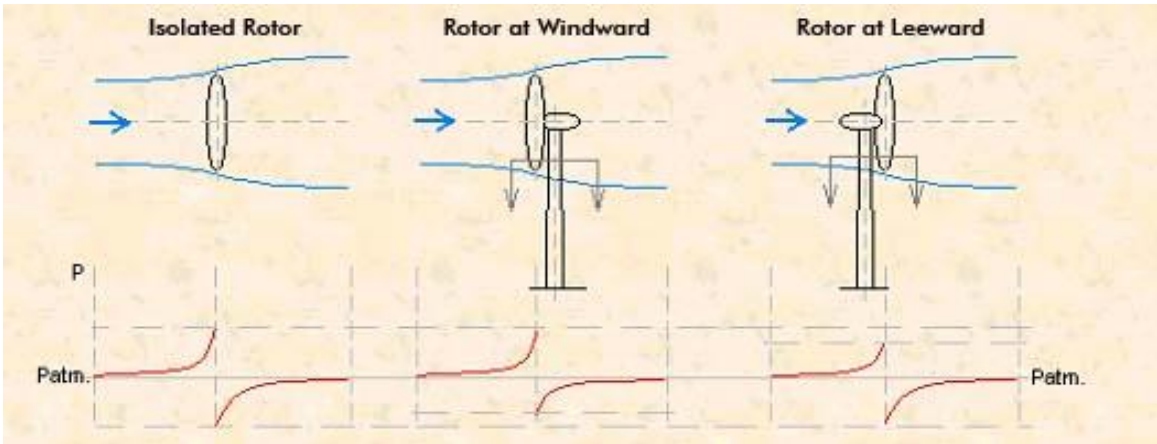
7.   Rotor Orientation

Figure 1

The eolic turbines can be placed following two configurations:

7.1 In front of the tower

This tower has the rotor opposite the wind, that is to say, in front of the tower.

The basic advantage of this kind of systems is that they have influence on the aerodynamic shadow of the tower. This is the most used configuration in aerogenerators design. However, this perturbation is present, altough it has a lower influence than in the other configuration. Therefore, when the rotor blades pass next to the tower, the capture of power goes down slightly.

The main disadvantage of this configuration is that it requires an orientation system, which keeps the rotor opposite the wind. Such systems can be active or pasive.

An active orientation system requires some direction sensors and motorized actuators which would guide automatically the rotor against the wind direction.

A pasive orientation system uses an stabilizing wing.

7.2 Behind the tower

In this configuration the rotor is found behind the tower, regarding the wind direction.

This system has the main advantage of not requiring any orientation device, but only if the rotor has been designed to follow pasively the wind direction.

Another additional advantage is the possibility to use more flexible materials for the blades. In this way, the structure of the tower does not suffer so high stresses due to the wind speed, since they are able to deflect it.

The main disadvantage is the wind power captured fluctuation when the rotor passes behind the tower, due to the aerodynamic shadows produced.

8.   Dragging and support effects

When a blade is placed along a perpendicular direction to that of the wind, it is affected by the dragging and support effects.

There are a lot of designs for the blades, but the basic geometry is usually the same: a rounded back (regarding the air flow) edge, called "leading edge", and a sharp front edge called "trailing edge".
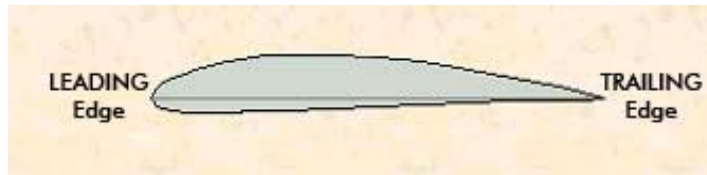

Figure 2

The term "rope of profile" is used to define the geometric place of the line which passes by these two points.

The air on the front side of the blade creates a lower pressure on the back side. That creates a force which lets the blade rotate. This is the support effect, which is perpendicular to the blade plane.
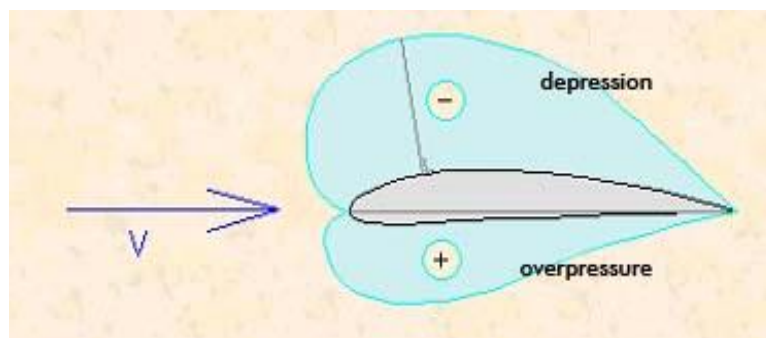

Figure 3

To represent the action of the air on any point of the profile, we have to take into account the local pressure coefficient, K_p:

$$K_p = \frac{(p - p_0)}{\frac{1}{2} * \rho * V_0^2} \qquad \text{[Ec. 45]}$$

Being p the pressure on the profile pressure and p_0, V_0 the pressure and velocity at infinite. Integrating those pressures we have the pressure force. This should be added to the forced produced by the air viscosity effect on the blade surface, that is to say, the force produced by the friction between particles of the surface and particles of the air, to finally obtain the total force or total aerodynamic action.

When considering this total force, we can divide it into its projections on the two perpendicular axis related to the direction of the air speed. In this way, the "supporting force" is obtained, the L perpendicular to this direction and the "resistance or dragging force", the D parallel to the same direction.

We have a symmetric aerodynamic profile in a flow of a non-compressible fluid with a null attack angle (angle between the incident air and the surface of the directional blades). In this situation some suctions at both sides of the profile will be created, with the same module, so the result will be null. If the attack angle increases in the same situation, an asymmetry appears, producing a descendent action. This same effect is obtained if keeping the atack angle null the profile is asymmetric.

For small attack angles, the supports increases almost linearly with an increase of the attack angle. This behaviour can be explained by the potential theory. However, for great attack angles, the support goes quickly down when the profile loses the limit film.

The aerodynamic resistance of a profile is the component parallel to the incedent flow of the pressure and air friction forces on the profile.
All support profiles support aerodynamic resistance, with minimum values for a samll attack angle. It increases following a parabolic with the aerodynamic load until it loses the limit film, creating a reverse velocities gradient.

The support coefficient is expressed in this way:

$$C_l = \frac{L}{\frac{1}{2} * \rho * S * V_0^2} \quad \text{[Ec. 46]}$$

L is the support force

S is the area of the plant view of the blade.

Another parameter is the dragging coefficient, which is defined as:

$$C_d = \frac{D}{\frac{1}{2} * \rho * S * V_0^2} \quad \text{[Ec. 47]}$$

Both parameters are characteristics of the shape of the profile. The support and resistance can be considered as applied on a particular point of the profile. Then, it is necessary to define the aerodynamic forces action completely, to specify the momentum around this point.

The momentum coefficient is defined as:

$$C_m = \frac{M}{\frac{1}{2} * \rho * S * C * V_0^2} \quad \text{[Ec. 48]}$$

C is the profile rope.

M is the aerodynamic momentum, considered as positive when it rises the profile.
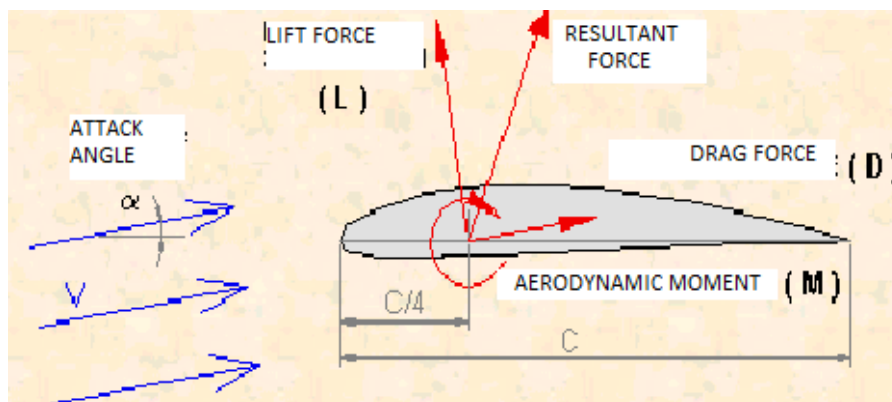
This coefficient depends on the considered point. Ususally, there is a point in the profiles called "aerodynamic center or focus", which has the property of keeping this coefficient constant for different attack angles. It also exists another characteristic point called "pressure center", where aerodynamic forces cut the profile rope and, therefore, the aerodynamic momentum is null with regards to this point.

Once these characteristic coefficients of the aerodynamic profiles have been defined, some relations among them will be studied.

So, we have: $C_l = f_l$ (Re, M, α); $C_d = f_d$ (Re, M, α); $C_m = f_m$ (Re, M, α), where Re is the Reynolds number, M is the Mach number and α is the attack angle.

The Mach number is the quotient between the relative incident velocity and the local sound velocity: M = V /a, (a is usually used for the air at room temperature 340 m/s). For low Mach numbers, until 0.3, the air can be considered as non-compressible, losing thus the dependency of the characteristics of the profile. That is to say:

$$C_l = f_l \text{ (Re, } \alpha); C_d = f_d \text{ (Re, } \alpha); C_m = f_m \text{ (Re, } \alpha) \qquad \text{[Ec. 49]}$$

For higher values of this parameter, until 0.8<M<0.9, the compressibility starts to affect, creating some transversals waves which increases the aerodynamical ones.

The Reynolds number is defined by the quotient between the convection forces due to velocity and the viscosity forces. This number controls the laminar or turbulent regime of the fluid field, being a decisive parameter. For low Reynolds numbers, any perturbation is reduced by viscosity and flow keeps itself laminar. Over a critical value, any perturbation produces the transition between these two states. Over this value, called critical Reynolds, the results obtained are similar, losing the dependency of this parameter.

It is usually considered that the optimum attack angle is that whose relation between the aerodynamics frequency Cl/Cd is maximum. The support angle is that whose support coefficient becomes Cl, zero. For asymmetric profiles, this value usually corresponds to negative angles. It can be seen in this figure:
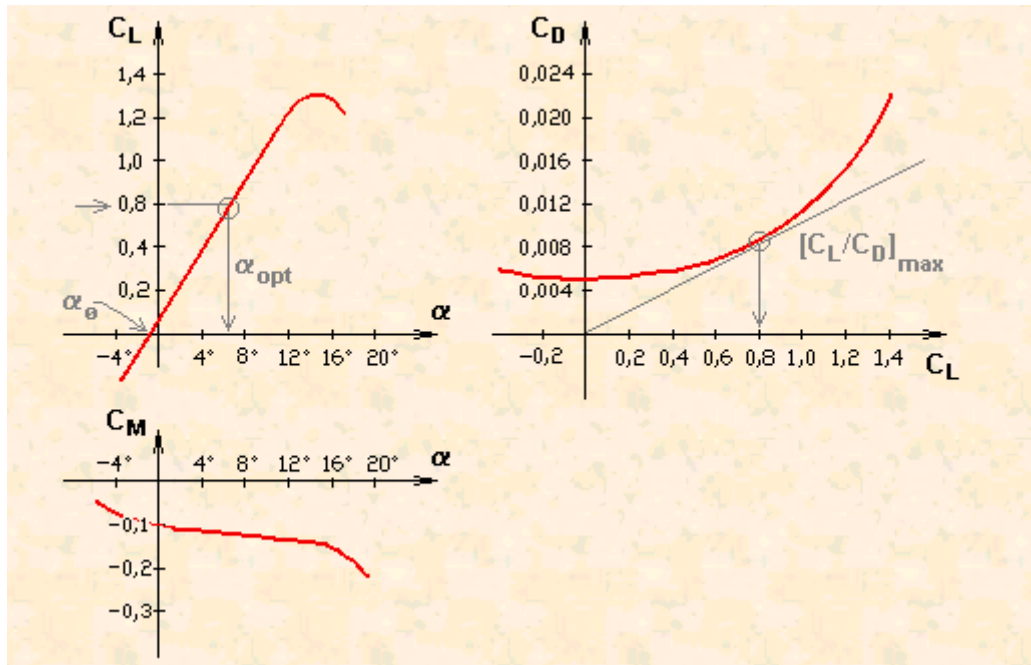
An important point when choosing the profile is to avoid those which give a maximum value (peak value) when increasing the attack angle, since it produces the limit film to be lost, with the purpose of avoid vibrations while working.

Taking into account all these considerations, very thin profiles are usually chosen. However, we can not forget that the blades structure must suffer very high charge conditions, both aerodynamics and mechanical. So, we have to reach a compromise situation between the maximum transversal area required to have an optimum efficiency and the minimum which can support the stresses produced.

9. Trail effect

An aerogenerator is always going to create a trail along the wind direction.
This trail is a long wind much more turbulent and slow than the wind that produces
it. This trail can be appreciated using some smoke in the air which passes through the
turbine. As it can be seen in the next figure:

9.1. Loosing factor by finite size

An effect that appears in the rotor blades is the "blade point effect
or   finite size effect", which consists on the deviation of the flux lines from
the inner side of the profile (lower   air   velocity,   higher   pressure)
towards   its   outer   side (higher velocity, lower pressure).

Then, tangential forces in this region are affected, as axial forces are.

There are different theories about this topic, and corrections must be
introduced in the results obtained from the movement quantity theories.

One of them is that by Prandlt, which consists on introducing a factor given
by:

$$F = \frac{2}{\pi} * ar\cos\left(e^{-f}\right) \qquad [\text{Ec. 50}], \text{ where } f = \frac{B}{2} * \frac{(R-r)}{R * sen\phi} [\text{Ec. 51}]$$

Another method to describe this phenomenom shows that we have to add to the dragging force another suplementary force, called induced dragging, so the profile dragging coefficient, C_d, will be: $C'_d = C_d + C_{di}$. To assure the same support than in the case of the finite size, the incidence angle should be: $a' = a + a_i * \beta * f' = f + f_i$. It can be demonstrated that these values obtained come from this equation:

$$C_{di} = \frac{S}{L^2} * \frac{C_l^2}{\pi} \; ; \; \phi_i = \frac{S}{L^2} * \frac{C_l}{\pi} \quad \text{[Ec. 52]}$$

Where S is the surface in the plant view of the blade and L the longest dimension.

The first of these two theories will be applied to make calculations easy. Then, the F factor will be added in the stresses, respectively dT, dC and dP, of the equations of the previous point:

$$dT = 2 * \pi * \rho * V_1^2 * 2 * K * (1 - K) * F * r * dr \quad \text{[Ec. 53]}$$

$$dC = 4 * \pi * \rho * V_1^2 * \Omega * K' * (1 - K) * F * r^3 * dr \quad \text{[Ec. 54]}$$

$$dP = 4 * \pi * \rho * V_1^2 * \Omega^2 * K' * (1 - K) * F * r^3 * dr \quad \text{[Ec. 55]}$$

On the other hand, we have to remind that, when analizing the triangle velocities it is obtained:

$$tg\phi = \frac{V_1 * (1 - K)}{\Omega * r * (K' - 1)} \quad \text{[Ec. 56]}$$

$$sen\phi = \frac{V_1 * (1 - K)}{V_r} \quad \text{[Ec. 57]}$$

1. Practical exercise 1:Study of the power generated by the aerogenerator depending on the wind speed

1.1. Objective

As seen before, one of the factors which has more influence in the available wind power is the speed. For that reason, we will study the influence of this factor in a practical way. It is desired to demonstrate how the speed of the wind influences on the working of the rotor.

1.2. Required elements

- Fan.

- Rotor of six blades.

- Anemometer.

- Speed sensor.

- Voltage probe (Wattmeter).

- Current probe (Wattmeter).

- Loads module.

- Temperature sensor, J type thermocouple.

- Regulator.

- Control System (SCADA).

1.3. Explanation

Power changes with air density, the rotor area and the cube of wind speed. In order to study the power as a function of the wind speed, we will try to keep the density and the area of the rotor constant. We will use a density value of 1225 Kg/m^3. The fan speed will be changed and, for each fixed speed, every data will be taken: voltage, current, rotation speed.

1.4. Practice development

Make sure the fan is turned off before starting the practice. Afterwards, follow the steps described below:

1) Turn ON the main interface.

2) Put the selector of the DC module to position 4.

3) Turn ON the DC module.

4) Run the SCADA by EDIBON, EEEC.exe. Make sure that the PC is connected to main interface via the SCASI cable.

5) Set *Meas* selector to Before.

6) Turn on the fan.

7) Fix a low fan speed, it will be gradually increased.

8) Take speed values. Write down the voltage, current and rotation speed given by the software in the table.

9) Increase the fan speed.

10) Repeat steps 8 and 9 at least 6 times.

11) Turn off the fan.

1.5. Results and tables

V$_{wind}$ (m/s)	I_dc (A)	V_dc(w)	N (rpm)

Comment how the wind speed influences on the captured power.

2. Practical exercise 2: Determination of the typical parameters of the Aerogenerator

2.1. Objective

The aim of this practice is to verify and to understand the functioning of the aerogenerator, by <u>determining the I-V curve</u> and the typical operational parameters, as the short circuit current (Isc), the open-circuit voltage (Voc), as well as the maximum power (Pmax).

2.2. Required elements (components)

Wind power equipment.

2.3. Development of the practice

1) Connect the single-phase power supply and put the interface in operation. Do that after verifying that every sensor is correctly connected to it.

2) Turn ON the main interface.

3) Turn ON the DC module.

4) Run the SCADA by EDIBON, EEEC.exe. Make sure that the PC is connected to main interface via the SCASI cable.

5) Set *Meas* selector to Before.

6) Turn on the fan.

7) Verify that the position of the DC-load rheostat is at maximum

resistance (LEFT POSITION).

8) Place the DC-load selector to position 2.

9) Disconnect the DC-lamps which are connected in parallel with the rheostat (LOWER SWITCH POSITION).

10) Turn the After/Before MEAS switch to Before.

11) Move the controls AVE-1 to the maximum position, in this way we will obtain the maximum air speed. Write down the values measured by the current sensor I_DC, the voltage V_DC and the air speed SVA-1.

12) Change the position of the load rheostat approximately to the 90% of R and write down the values of the parameters obtained.

13) Repeat the point 12 with an approximate increase or decrease of 10% of the load rheostat value until the 0% of R is reached. This is the short-circuit point of the solar panel.

14) In order to obtain the open circuit voltage of the panel, place the DC-Load selector in position 1.

2.4. Results and tables

Write the results according to the following table:

Position R(%)	I(Amp)	V(Volts)	Air Speed m/s
max			
<<<			
<<			
min			
0			

Isc=   Voc=

Draw the curve I-V.

3. Practical exercise 3: Determination of the maximum power output of the Aerogenerator

3.1. Objective

The aim of this practice is to obtain the maximum performance point or Pmax of the aerogenerator at different levels of air speed.

3.2. Required components

Wind power equipment.

3.3. Development of the practice

1) Connect the single-phase power supply and put the main and DC module interfaces in operation, after verifying that every sensor is correctly connected to it.

2) Turn ON the main interface.

3) Put the selector of the DC module to position 4.

4) Turn ON the DC module.

5) Run the SCADA by EDIBON, EEEC.exe. Make sure that the PC is connected to main interface via the SCASI cable.

6) Set the *Meas* selector to Before.

7) Verify that the position of the DC-load rheostat is at maximum resistance.

8) Place the DC-load selector in position 2.

9) Disconnect the DC lamps which are connected in parallel with the rheostat.

10) Turn the After/Before switch to Before.

11) Move the control AVE-1 to the maximum position, obtaining thus the maximum air speed.

12) Slowly change the load rheostat position from 100 % down to 0%, looking for the approximate point where the highest value of power (VxI) is obtained, (or first, trace the curve I-V to obtain the maximum point). Write down the values measured by the sensors of current I_DC, voltage V_DC and air speed SVA-1.

13) Repeat the point 12 with the relatively proportional declines of the control AVE-1 in such a way that the 4 points of measurement between the maximum and minimum values and air speed can be obtained.

3.4. Results and tables

R = (0-100) %. Write the results according to the following table.

AVE-1	Pmax(W) (IxV)	SVA-1 (m/s)
Max.		
<<<<<<<<<		
<<<<<<<<		
<<<<<<<		
<<<<<<		
<<<<<		
<<<<		
<<<		
<<<		
<<		
Min.		
OFF		

Draw the graph Pmax-Air_Speed according to the air speed or maximum efficiency curve.

4. Practical exercise 4: Study of the power generated by the aerogenerator depending on the incident angle

4.1. Objective

Once the behavior of the efficiency of the aerogenerator with the wind speed has been analyzed, it would be interesting to analyze the influence of the air incident angle on the power captured by the rotor. It seems easy to understand that the efficiency of the aerogenerator will depend on the incident air, what produces a different speed rotation in the rotor.

4.2. Required elements

- Fan.

- Rotor of six blades.

- Anemometer.

- Speed sensor.

- Voltage probe (Wattmeter).

- Current probe (Wattmeter).

- Loads module.

- Temperature sensor, J type thermocouple.

- Regulator.

- Control System (SCADA).

4.3. Explanation

There are two ways of carrying out this exercise:

- In the first one, for a fixed fan speed, we can put the rotor in a fixed angular position with regards to the incident air, and take data (the same ones as in the first practice). Then, we can represent the captured power against the angular position of the rotor. Repeat the process for different fan speeds, that is to say, for different wind speeds.

- In the second one, once you have made the first one, you can measure data for a fixed angular position of the rotor changing the air speed. You can obtain the power against air speed for a fixed angular position. Repeat the same process for different angular positions.

Important: In order to fix the angular position of the rotor in the tunnel, we will use the black hexagonal screw: to change this position we just need to unscrew it, put it in the new position and screw it again.

4.4. Practice development

Before starting the practice, make sure the fan is turned off. After this, follow the steps described below:

1) Turn ON the main interface.

2) Put the selector of the DC module to position 4.

3) Turn ON the DC module.

4) Run the SCADA by EDIBON, EEEC.exe. Make sure that the PC is connected to the main interface via the SCASI cable.

5) Set the *Meas* selector to Before.

6) Turn on the fan.

7) Fix a low fan speed, about 3m/s.

8) <u>Set an angular position for the rotor</u>.

9) Take the speed value. Write down the voltage, current and rotation speed given by the software in the table.

10) Change the rotor angular position.

11) Repeat step 9.

12) Turn the fan off.

<u>Important: if you want to proceed as in the second case, you have to take</u> <u>different measurements for the same angular position at different fan speeds.</u>

4.5. Results and tables

After any test you should analyze the relation between the power and the angular position of the rotor. It would be good if changes when the fan speed varies, for a fixed angular position, were studied as well.

V_{wind} (m/s)	I_dc (A)	V_dc (Volts)	Angle position (degrees)	N (rpm)

Also, we can try to obtain the characteristic curve of the rotor, which is shown in annex 2.