# EOLIC ENERGY:MAIN ASPECTS

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## Abstract.

We show to graduate and undergraduate students of Physics and Engineering the basic physical principles responsible to the generation of electric energy using wind power ("*eolic power*"). Only horizontal axis turbines will be analyzed.

## (1) Wind Power Passing by the Turbine.

Historically, wind power was used, for instance, by sails, windmills and wind pumps, but today it is mostly used to generate electricity.(1-3) Will be analyzed only *horizontal axis wind turbines* (see Figures 1 and 2).

**Figure 1. Horizontal-axis wind turbine in a wind tower.**

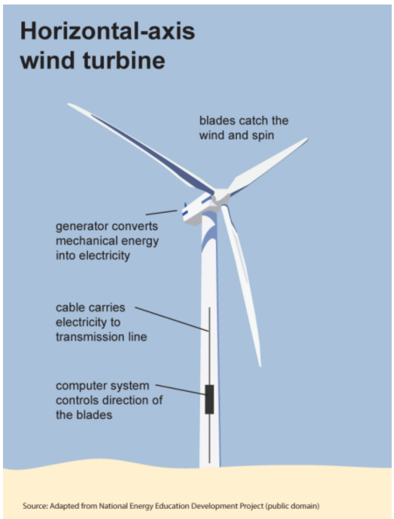


**Figure 2. Details of the wind turbine.(3)**

The wind turbine rotates around the **vertical tower axis** in order to always capture the wind arriving in the frontal direction. **Figure 2** shows the wind tube passing by the area A swept by the turbine blades.

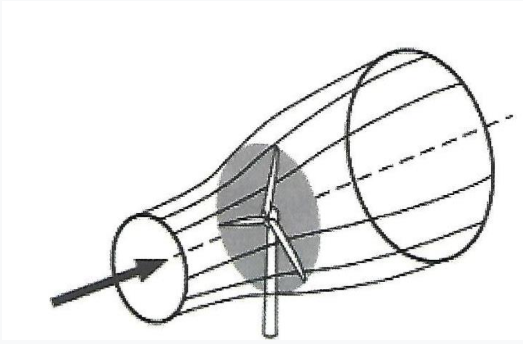

**Figure 2**. **Region swept by the wind. The turbine area A is seen as a grey disk.**

If an air mass quantity M (kg) pass by the turbine with velocity V (m/s) the kinetic energy E(Joule) passing by the turbine is

$$E = (1/2)MV^2 \qquad (1).$$

Thus, if M takes a time Δt (s) to pass by the turbine a rough estimation of its **power** P (Joule/s) is given by,

$$P = E/\Delta t = (1/2)(M/\Delta t)V^2 = (1/2)\ \Phi\ V^2 \qquad (2),$$

where Φ is the air mass flux (kg/s) that passes by the turbine area A($m^2$). If ρ is the air density (kg/$m^3$) **Eq.(2)** becomes, putting Φ = ρV,

$$P = (1/2)\rho AV^3 \qquad (3).$$

In this way power estimations P are given, for instance, by semi empirical equations like

$$P = (1/2)\pi\rho R^2V^3C_p(\lambda) \qquad (4),$$

where the *coefficient* $C_p(\lambda)$ is a function of λ = ΩR/V.[(4)]

In **Section 2** we show how the wind power P can be transformed in rotational energy by the turbine blades. Finally, in **Section 3** is shown how this rotational energy is transformed in electric energy.

## (2)Blades Rotation due to the Wind.

The turbine blades rotates when submitted to wind forces that depend of the blades profiles. For simplicity, these forces will be estimated assuming that blades cross sections are similar to profiles of airplanes aisles.[4,5] In **Figure 3** are seen the air flow lines around the blades cross sections. In this figure are shown the wind forces $\mathbf{f} = \mathbf{f}_\perp + \mathbf{f}_\parallel$ on the blades: $\mathbf{f}_\perp$ perpendicular to the profile and $\mathbf{f}_\parallel$ along the profile.

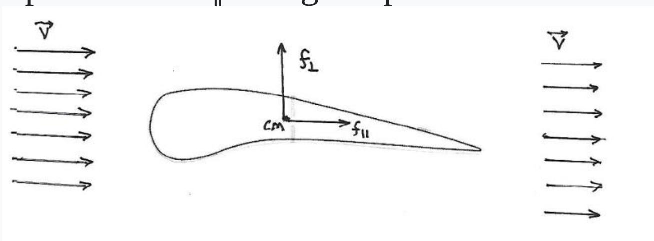


**Figure 3. Aerodynamical blades cross sections and forces $f_\perp$ and $f_\parallel$.**

As usually $\mathbf{f}_\parallel$ are very small[5] they will be neglected. In **Figure 4** are seen the resultant perpendicular forces $\mathbf{F}_\perp$ on the blades surfaces.

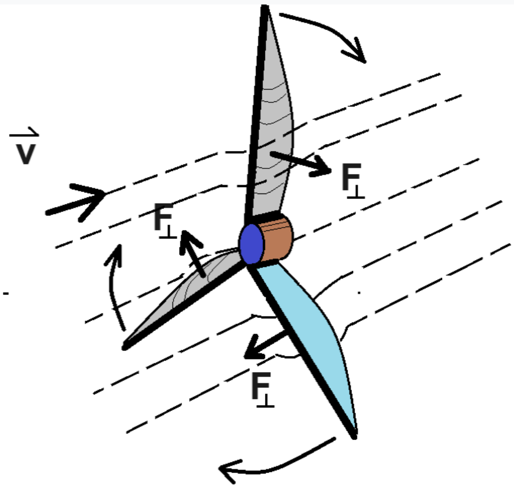

**Figure 4. Perpendicular resultant forces $F_\perp$ on the blades.**

The torque $\boldsymbol{\tau}$ of $\mathbf{F}_\perp$ on each blade, around the central rotational axis of the turbine, is given by

$$\boldsymbol{\tau} = \mathbf{R} \times \mathbf{F}_\perp = \boldsymbol{\varphi}\, R\, F_\perp \qquad (4),$$

where R is distance of the blade center of mass from the turbine rotational axis and $\boldsymbol{\varphi}$ the unit vector along this axis. Let us indicate by I the turbine moment of inertia (with 3 blades) around the rotational axis.

Now, let us assume that the turbine is at rest and the wind begins to pass by the turbine. When it begins to rotate its angular rotation $\omega$ begins to increase, given by $\omega = 3\tau/I$ .When the wind velocity reaches a maximum constant velocity V the angular rotation $\omega$ becomes $\Omega$ given by

$$\Omega = 3RF_\perp/I \qquad (5).$$

Assuming blades as aero dynamical aisles $F_\perp \approx \pi L\rho V^2$ [5] where L is the blade length, ρ the air density and R ≈ L/2. Thus we get, from Eq.(5),

$$\Omega \approx (3\pi/2)(\rho L^2V^2/I) \qquad (6).$$

To estimate I we take, for simplicity, blades as rectangular plates, each one with $I \approx (4/3)ML^2$, where M is the blade mass. Thus, from **Eq.(6)**:

$$\Omega \approx (4\pi/2)(\rho V^2/M) \approx \pi (\rho V^2/M) \qquad (7).$$

As $\rho_{air} \approx 1.3\ 10^3$ kg/m$^3$ [6] and putting M ~ 10 Ton = $10^4$ kg[7] we get

$$\Omega \approx 0.41\ V^2 \qquad (8).$$

For *moderate breezes*, that is, V ~ 20 km/h ~ 5.5 m/s we have, according to **Eq.(8),** Ω ~ 124 rad/s in fair agreement with the observed value Ω ~155 rad/s.[8] For *hurricanes,* when V ~100 km/h ~ 30 m/s, we estimate Ω ~370 rad/s, in good agreement with observed Ω ~ 344 rad/s.[8]

Note[8] that more efficient turbines work for wind velocities V in the interval $V_{min}$ ~ 12-14 km/h < V < $V_{max}$ ~ 90 km/h.

**(3)Electric Energy Generated by the turbine and Energy efficiency of a wind generator.**

As we seen above, wind energy depends of the mass M and the square of the wind speed $V^2$ according to **Eq. (1).**

The maximum wind power, considering the air flow (**Eq.(3)**), depends on the air density (ρ). We can estimate the density of air using the ideal gas equation

$$\rho = P/RT \qquad (9),$$

P the atmospheric pressure, T the temperature and R the gas constant.

Therefore, in places where atmospheric pressure is low or at higher temperatures, there may be significant changes in air density, and consequently, a decrease in wind power. For example, at 2 km above sea level, the power of a wind turbine decreases around 21% [9]. And for temperatures above 30° Celsius, power can decrease by around 5% [9].

**Betz Efficiency**

One of the first theories about the amount of energy that could be extracted by blades in fluids was developed by Albert Betz,[9] in 1920.

Using conservation of momentum, the maximum energy that we can extract from a wind turbine is equal to the kinetic energy of the wind that crosses the circle formed by the area of the propellers. But, as the wind still has kinetic energy after passing through the propellers, not all energy can be removed from the winds.

According to Betz(9), the efficiency of a wind generator could not exceed 59%, that is, at most, 50% of the wind energy could be transformed into rotational kinetic energy in the propellers.

In current wind systems, the efficiency of the conversion stages can be divided into the following steps:

1) Kinetic energy of winds in rotational energy of propellers ~ 40%
2) Coupling (gears) of the propeller shaft to the generator ~ 95%
3) Generator electromechanical conversion ~ 95%

**Overall average ~ 35%.**

Therefore, in a typical wind turbine, around 35% of a wind kinetic energy is converted into electrical energy.

**(4) Electromagnetic generator system.**

There are several types of electrical generators. For example, an electric motor can also be used as generator, transforming mechanical energy into electrical energy, like the fan motor we use as a wind generator set up in our laboratory.

Most wind generators use neodymium magnets as sources of magnetic fields(12). They have the advantage of being light, having high magnetic field values and not requiring external sources of electric current.

There are also no energy losses due to the joule effect, unlike electromagnets, increasing conversion efficiency.

The operating principle of an electromagnetic generator is based on Faraday´s law induction: the variation of a magnetic field through coils induces an electric current. The **Figure 5** shows the schematic of a magnet rotating in the vicinity of coils, with the respective voltages induced. In this generator, we have a magnet rotating next to 3 coils. This type of generator is called three-phase synchronous, that is, the alternating current is synchronizes with the rotating frequency.

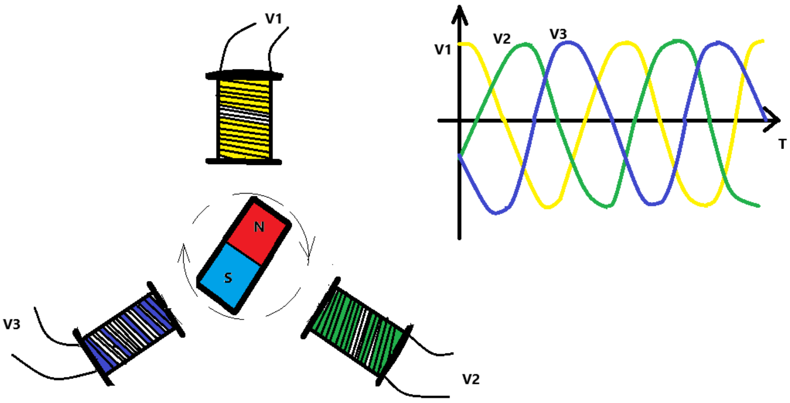


**Figure 5.** **Example of a three-phase synchronous generator.**

Another example of an electromagnetic generator is shown in **Figure 6.** In this case, unlike the previous example, the magnets are static and the loop is forced to rotate.

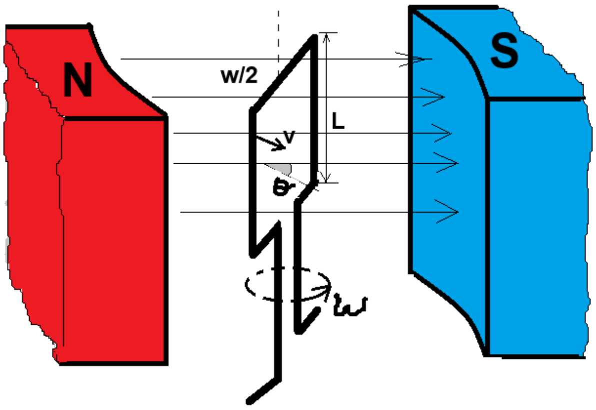


**Figure 6.** Magnets are static and the wire is forced to rotate.

The charges on the wire, located in the vertical direction, move in the magnetic field, they generate a force parallel to the wire, responsible by an electric current. The induced electromotive force **ε(t)** is given by

$$\boldsymbol{\varepsilon(t) = 2.B.l.v.\sin\theta}, \qquad \text{where } \theta = \omega t \qquad (9).$$

In our didactical laboratory (LaboDemo/IFUSP) we have a small wind turbine seen in **Figures (3a)** and (**3b**). In **Fig.(3a)** we have a frontal photo of this turbine and in **Fig.(3b)** a rear photo.

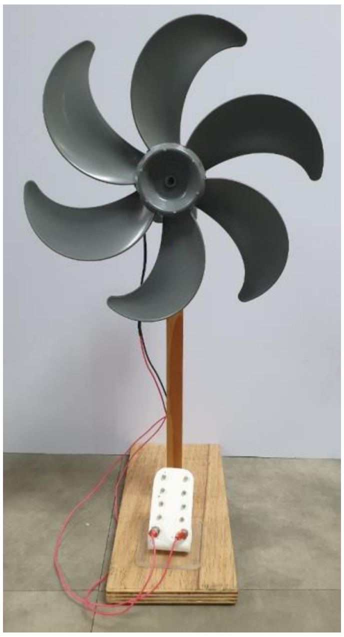

**Figure (3a).** Wind generator
(front view).

**Figure (3b).** Wind generator
(rear view**).**

Our wind generator was assembled with fan blades and a 12 volts, 15 watts DC motor. At our Laboratory we use a manual fan, seen in **Figure (3c)** and **(3d)**, to produce wind and, as an electric generator a set of LEDs is connected that drives the electric generator.

**Figure (3d). Manual fan**
**(front view).**

**Figure (3c). Manual fan**
**(rear view).**

The kinetic energy of the wind, transfers rotational kinetic energy to the generator. In turn, the generator transforms rotational kinetic energy into electrical energy which lights up the LEDs connected to the generator (see **Figure (3e).**

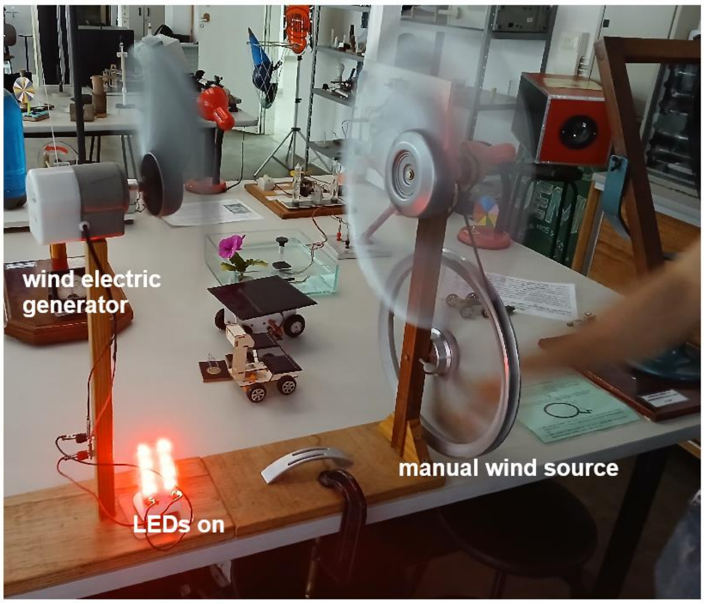


**Figure (3e). Manual fan and wind generator in operation.**

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