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BLADE AERODYNAMIC DESIGN AND ANALYSIS AS FIRST STEP TO ACHIEVE THE EXPECTED POWER PERFORMANCE OF A SMALL WIND TURBINE

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Abstract- For the last two decades the wind power industry has rapidly increased in Europe becoming one of the most economic renewable energy sources. For a good performance in the capture of the wind energy, one of the most important parts are the blades of the wind turbine. From simple designs for domestic wind turbines to the application of the last technology of aerodynamics for big aero-generators, research in blades (physical design, profile, materials, structure, etc.) is one of the major research fields in electric generation. Blades should be studied primarily from two points of view: the aerodynamic and structural one. Blade element momentum theory is normally used in the optimization process of blade design. In this paper, we present an introduction to the design of blades of a wind turbine for using in a low power and low cost wind generator.

Keywords: Blade, Design, Wind Turbine, BEM, Aerofoil, Wind Energy.

I. INTRODUCTION

For the last two decades the wind power industry has rapidly increased in Europe becoming one of the most economic renewable energy sources.

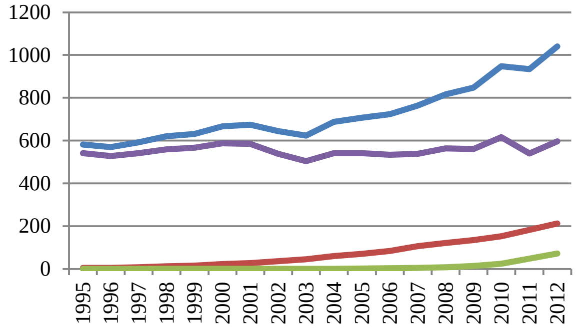

Figure 1. Renewable electricity net generation in Europe

In Figure 1, four different renewable generations in Europe are shown: in blue color, total renewable electricity net generation (with approx. 1040 TWh in 2012); in purple color, hydroelectricity electricity net generation (about 596 TWh in 2012); in red color, wind electricity net generation (about 212 TWh in 2012); and in green color, solar electricity net generation (approx. 71 TWh in 2012).

Particularly, in Spain, in 2011 the percentage of electricity obtained from wind power reached the 16.3%. The weight of this energy resource in power generation companies has grown steadily, becoming nowadays one of the most dynamic sectors of the Spanish economy [1].

From a more economical the point of view, there is a mean value for the costs of electricity production for all kinds of conventional electricity production and load profiles in 2010 which is 10.9 €ct to 11.4 €ct per kWh. The RWI (Rheinisch - Westfalischen Institute) calculated this on the assumption that the costs of energy production would depend on the price development of crude oil and that the price of crude oil would be approx. 23 US$ per barrel in 2010. In fact the crude oil price was about 80 US$ in the beginning of 2010, and 46 US$ at the end of September of 2015. This means that the effective costs of conventional electricity production still need to be higher than estimated by the RWI in the past. The following Table 1 arises for the costs of electricity production in newly constructed power plants in 2010 [2].

Table 1. Arise for the costs of electricity production

Energy source	Costs of electricity production €ct/KWh
Nuclear Energy	10.70-12.40
Brown Coal	8.80-9.70
Black Coal	10.40-10.70
Domestic Gas	10.60-11.80
Wind Energy Onshore	4.97-9.61
Wind Energy Offshore	3.50-15.00
Hydropower	3.47-12.67
Biomass	7.71-11.55
Solar Electricity	28.43-39.14

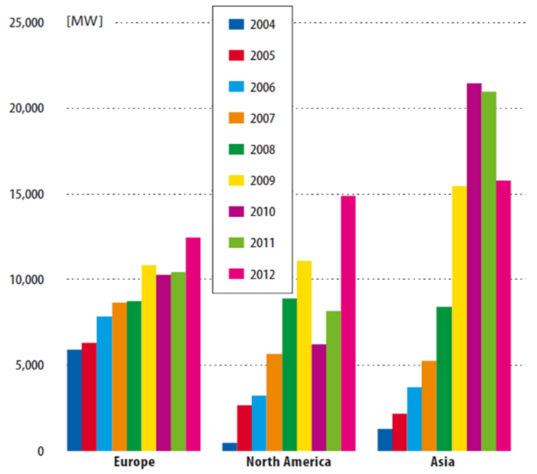

Figure 2. Annual installed wind power capacity in developed regions

Table 2. Total electricity consumption and wind energy production in EU in 2014

Total EU electricity consumption (TWh)	2,798
Onshore wind energy production (TWh)	254.3
Offshore wind energy production (TWh)	29.59
Share of EU consumption met by onshore wind	9.1%
Share of EU consumption met by offshore wind	1.1%
Share of EU consumption met by wind	10.2%

Installed wind power capacity is also increased year by year in developed regions, as we can see in Figure 2. Obviously, the rate of increment is not continue in time because different factors, where two important factors may be some political decisions about funding this renewable energy and crisis with other energies such as nuclear affairs [3].

The wind energy capacity in 2014 installed in the EU, particularly, would produce in an average wind year 284 TWh of electricity, enough to cover 10.2% of the EU's total electricity consumption [4], as it is shown in Table 2. In Figure 3, we can aldo see country by country, in Europe, the installed wind capacity by end of 2014 [4].

In a wind power generation, blades are the component designed to capture wind energy and transform it into mechanical power. In this way, the rotor of the alternator will rotate at a certain angular velocity and produce a certain mechanical torque. Blades are one of the fundamental elements of a wind turbine. Blades greatly influence efficiency of wind turbines and they are the component subjected to greater efforts, making them the most likely to fail. Therefore, a good design of the blades of a wind turbine is critical to this.

One of the major research fields for wind turbine technology development is blade design optimization [5]. Blades should be studied primarily from two points of view: the aerodynamic and structural one. The first one is analyzed in order to generate the required power under the wind conditions that occur in the region where the wind turbine will be located, trying to get a good efficiency.

In the structural analysis we should check the resistance of the blade to the loads which it is subjected to. Both aspects must be taken into account to choose more technological factors, such as material or manufacturing process of the blade. This article mainly discusses the aerodynamic point of view.

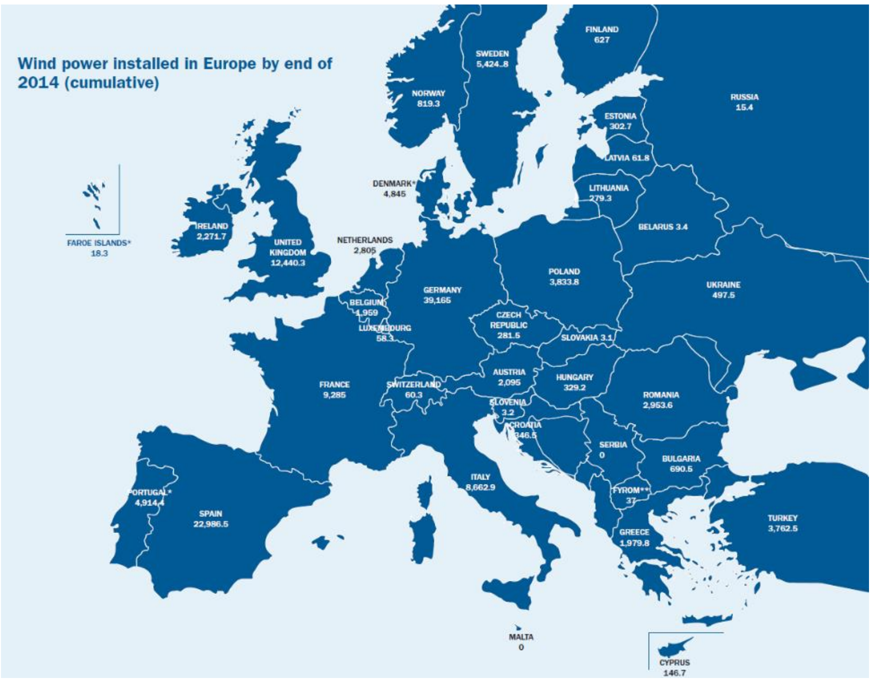

Figure 3. Wind power installed in Europe by end of 2014. Source: EWEA. The European Wind Energy Association, www.ewea.org [4]

II. STATE OF THE ART

There are three main factors that must be considered for blade design [6]. First, power extraction occurs mainly on the outer part of any turbine blade. Second, starting torque is generated mainly near the hub. Thirdly, thick aerofoil sections are not to be used for small turbine blades as their low-Re (Reynolds number) performance is generally very poor at high angles of attack.

Although there are many types of wind turbine, the fundamental components of one of them generally are the following: blades, to capture energy from the wind; electric generator, which converts mechanical energy into electrical energy; hub, shaft and gear box, to transmit mechanical power to the generator and adapt the rotation speed; power electronics and other electrical systems, to transform the generated electrical energy, giving it a suitable condition for use (direct consumption) or insertion into the power network; yaw system, to keep the turbine towards the wind; control system, for regulation of speed and generated power; and tower.

A. Blades

Blades are the component designed to capture wind energy and transform it into mechanical power. The shape, arrangement and number of blades vary greatly depending on the turbine model in question. Usually, they have an aerodynamic shape, which makes the incident wind generates force pairs that move the rotor and capture part of the energy of wind.

Blades support large and highly variable loads, because of the random nature of the wind resource. Therefore, it is important to ensure that mechanical failure will not be caused by fatigue. Moreover, blades are exposed to the weather elements, so they must resist damages from them, such as corrosion.

Typically, rotor blades are made of composites including glass and/or carbon fibres as reinforcement, resins, sandwich core materials, coatings and lightning conductors. The internal part (called spar) is made of many layers of inorganic fibres and thermoset resins and the outer part (shell) is a sandwich structure made of a foamed core. In the small wind turbines, the previous option is also the most chosen, although there are more possibilities and flexibility.

B. Axis Position

According to the orientation of the axis of the turbine, we can classify them into two groups: horizontal axis wind turbines (HAWT) and vertical axis (VAWT). Horizontal axis generator, HAWT, is the most widespread. The horizontal axis wind turbines tend to achieve higher performance than the vertical axis; this is the main reason research efforts have focused more on them than on the turbines of vertical axis.

C. Position of the Rotor Respect to the Wind

This classification makes sense only if we talk about HAWTs. A generator with horizontal axis can be positioned (its rotor) upwind and downwind.

The most common position is the windward (upwind). In this position, we get the wind reaches the rotor blades without having been disturbed by the tower.

D. Number of Blades

There are many options for the number of blades of a wind turbine. In general, a larger number of blades causes the wind turbine has higher torque, but lower rotation speed.

The condition of the low axial velocity at the high rotational speed for the turbine with high blade number could be the blockade effect created by the number of blade area interacted with fluid. For the turbines with lower blade number, the blockade effect is relatively less. This makes the lower bladed turbines possible to obtain a relatively higher attack angle at the high rotational speed than that of the high-bladed turbine [7]. The most common model is the three-blade model.

E. Blade Geometry

The geometric shape of the blade is decisive for calculating the power of the wind turbine. A blade with a good design can have large efficiencies, while a poor design will not capture more than a small part of the energy carried by the wind.

The geometry of the blades usually varies along the radial direction. In addition, blades often have a certain torque; that is, the blade is twisted on itself. With a given torque we increase the efficiency of the blades.

So we can say that the geometry of the cross section of the blade is different for each value of r, as it shows in the Figure 4, where a differential radial length dr can be considered constant.

The shape of the cross section of the blade, along all values of r from zero to R, completely defines the geometry of the blade. In order to define geometrically a section, we identify three variables: the profile to use, chord and torsion. Each cross section is shaped like an airfoil, as shown in Figure 4.

III. DESIGN OF BLADES

Blade aerodynamic design and analysis is the first step to achieve the expected power performance. The blade design parameters include airfoil shape, design attack angle, design tip speed ratio, and rated wind speed, which are to be considered in the wind turbine blade aerodynamic design stage. The selection of these blade parameters is often based on blade element momentum (BEM) theory [8]. BEM theory usually is used for evaluating the forces on the wind turbine in its design and optimization [9].

Blade Element Momentum Theory equates two methods of examining how a wind turbine operates. The first method is to use a momentum balance on a rotating annular stream tube passing through a turbine. The second is to examine the forces generated by the aerofoil lift and drag coefficients at various sections along the blade. These two methods then give a series of equations that can be solved iteratively [10].

Consider the stream tube around a wind turbine shown in Figure 5. Four stations are shown in this figure: 1, some way upstream of the turbine; 2, just before the blades; 3, just after the blades; and 4, some way downstream of the blades. Between 2 and 3, energy is extracted from the wind and there is a change in pressure as a result.

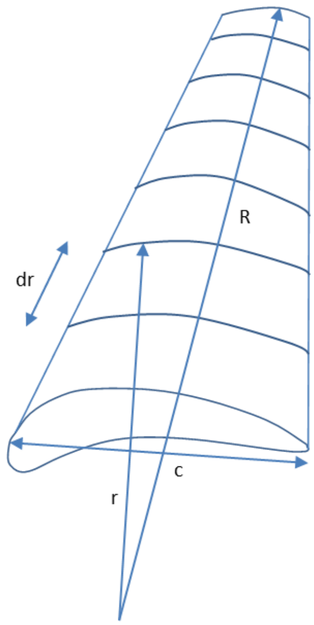

Figure 4. Variation of blade geometry in the radial direction

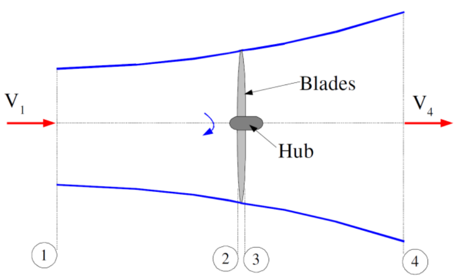

Figure 5. Axial stream tube around a wind turbine [10]

Assume $p_1 = p_4$ and that $V_2 = V_3$. We can also assume that between 1 and 2 and between 3 and 4 the flow is frictionless so we can apply Bernoulli's equation. So, we can operate in the following way:

$$p_2 - p_3 = \frac{1}{2}\rho\left(V_1^2 - V_4^2\right) \quad (1)$$

Noting that force is pressure times area we find that:

$$dF_x = (p_2 - p_3)dA \quad (2)$$

$$dF_x = \frac{1}{2}\rho\left(V_1^2 - V_4^2\right)dA \quad (3)$$

Define a as the axial induction factor as:

$$a = \frac{V_1 - V_2}{V_1} \quad (4)$$

It can also be shown that:

$$V_2 = V_1(1-a) \quad (5)$$

$$V_4 = V_1(1-2a) \quad (6)$$

Substituting yields:

$$dF_x = \frac{1}{2}\rho V_1^2\left[4a(1-a)\right]2\pi r dr \quad (7)$$

Further blade design optimization is essential to achieve a better power performance. Previous research indicates that wind turbine blade design optimization has been carried out based on BEM theory, generally in an iterative way [11]. Bak's research work on the sensitivity of key parameters in wind turbine blade design on power performance demonstrated that the design tip speed ratio should be between 5.5 and 8.5 depending on the airfoil performance and the application of the wind turbine [12].

The selected profile in our design has been NACA4412 because it is similar to others used in wind turbines, and we choose a three-blade model for a wind turbine of 400 W with nominal speed of 10 m/s. We obtain that the longitude of each blade will be R=0.82 m.

For the design optimal situation we use the BEM method and the following results for the optimal chord of these blades.

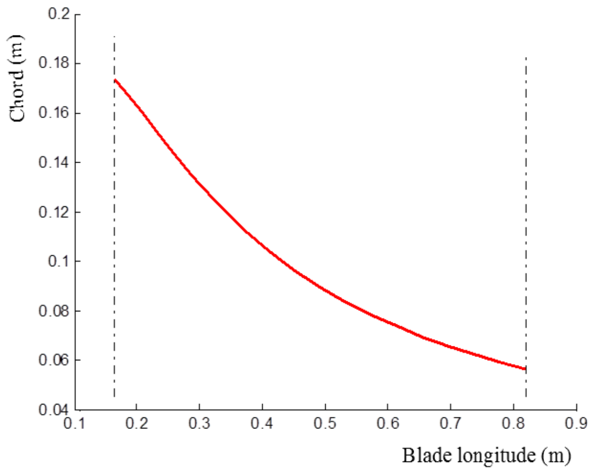

Figure 6. Optimal chord for the selected blades

IV. CONCLUSIONS

One of the most important parts of wind turbines are the blades. A good design of this component may cause a good efficiency in the power generation or just the opposite. We have designed a blade geometry based in NACA profiles for a low power wind generator of 400 W and presented some results of calculations.

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BIOGRAPHIES

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