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VARIABLES CHOSEN FOR THE AEROFOIL WORK IN AN OPTIMAL ANGLE OF ATTACK

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Abstract- A wind turbine has different parts and several of them can be considered as fundamental. One of these are the blades that are an essential element for a good performance. Apart from the material of the blade, size, and other variables, a good design of the blade is crucial. In this paper, BEM method is used to implement this design. This method uses, among others, the lift and drag coefficients of each aerofoil element with the local geometry and design flow conditions to predict aerodynamic performance.

Keywords: Wind Turbine, Wind Generation, Blade, BEM Method, Lift, Drag Coefficients.

I. INTRODUCTION

In some countries wind energy is the new source of electricity with a big and fast expansion, while in others it is just a problem to find locations and grants for new installations. But there is no doubt that wind generation is one of the future energies. It is presently the renewable energy with the highest power generation in the world. In the one hand, it needs some considerable budget for the beginning and a good location that allows the generation of a minimum quantity of energy during a period of time, what can be considered as a disadvantage. This last requirement of a good location is not very difficult to find, and less if we consider off-shore locations; but it has the difficulty of maintaining ecological conditions of the area where the wind turbines will operate. The other requirement, the initial high budget, is reduced if we consider a low power wind turbine. Moreover, these types of wind turbines (those that generate low power) are smaller and the possible locations are very more numerous. Therefore, those "disadvantages" are not insuperable, particularly in the cases of small wind turbines.

For these small wind turbines, there are several classes or types, from horizontal-axis to vertical-axis and other classifications. But among all the classes of wind turbines, there are other elements that are important when we study the energetic and economic performances of a wind turbine. One of these elements is the shape of the blade.

Other factors, like political situation and planning, are also important and normally we cannot affect them. Wind emerged as the primary source of electricity in Spain for the whole of 2013. The Spanish Wind Energy Association (AEE) shared that 2013 proved to be a historic year for the wind energy industry. In fact, as the association stated, Spain is the first country in the world where wind is ranked as the technology that contributes most to the power demand coverage for an entire year. According to the 2013 advance report of the system operator Red Electrica de Espana (REE), the power demand coverage using wind was 20.9%, compared with 20.8% coming from nuclear; and wind power production during 2013 was 54,478 GWh, representing a 13.2% increase over 2012. But in the year 2014, the sector only installed 27 MW (Figure 1).

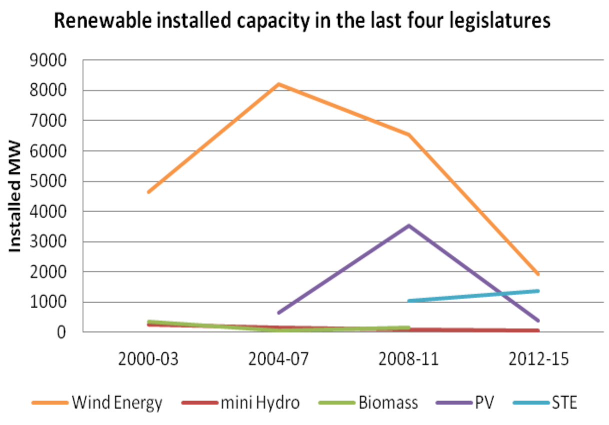

Figure 1. Renewable capacity installed in the last four legislatures in Spain. Source: CNMC, REE and AEE [1]

The calamity came in the year 2015, which closed as the darkest in the history of wind energy in Spain, with zero megawatts installed. This has not happened since the 80's, when a shy development of the sector started in our country, which was accelerated in the 90's and consolidated in the next decade, reaching 22,988 MW currently. Wind power production in the year was 47,721 GWh –5.8% below that of 2014–, and it covered 19.4% of electricity consumption, according to REE.

II. BLADES OF A WIND TURBINE

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.

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.

In large wind turbines, blades are normally manufactured in composite materials, where the most common option is to use fiberglass or carbon fiber reinforced by plastic resins such as epoxy. For smaller wind turbines, the previous option is also the most chosen, although there are more possibilities and flexibility.

III. BLADES 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 Figure 2, 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 [2]. Each cross section is shaped like an airfoil, as shown in Figure 2.

Some definitions may be useful at this point: the chord line is the reference line of the aerofoil, and it is the line connecting the most extreme points at the leading and trailing edges. The chord is the reference length of the aerofoil and it is measured along the chord line. The value of the chord dimension is the distance between the extreme leading and trailing edge points. All other dimensions are referenced to the chord. Most NACA aerofoils specify a leading edge radius to connect the upper and lower surface contours. The radius is struck from a line, intersecting the chord line at the leading edge, and which may be at the angle to the chord line. If so, then the angle is specified in terms of the slope of this line measured relative to the chord line.

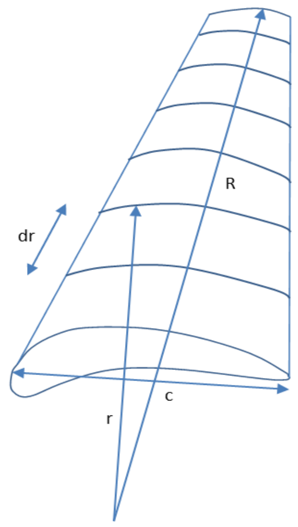

Figure 2. Variation of blade geometry in the radial direction

IV. BLADE DESIGN AND USE OF BEM

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 [3]. BEM theory usually is used for evaluating the forces on the wind turbine in its design and optimization [4].

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 [5].

Applying BEM methods to fixed pitch blades requires knowledge of aerofoil lift and drag at angles of attack exceeding the stall point.

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 [6]. 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 [7].

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 results are shown in Figure 3 for the optimal chord of these blades [8].

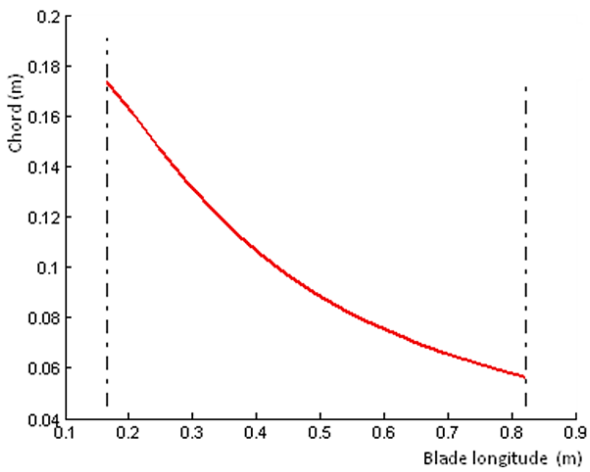

Figure 3. Optimal chord for the selected blades

V. LIFT AND DRAG COEFFICIENTS

It is common to speak of lift per length unit, L, and drag force per length unit, D. The length, which referenced forces are to, is radial, that is, perpendicular to the plane of the flow around the profile. This is a suitable formulation for forces because both the blade geometry and flow conditions vary in the radial direction. Therefore, D and L will also be functions based on r.

Lift force can be defined to be perpendicular to direction of the oncoming air flow. The lift force is a consequence of the unequal pressure on the upper and lower aerofoil surfaces.

Drag force can be defined to be parallel to the direction of the oncoming air flow. The drag force is due both to viscous friction forces at the surface of the aerofoil and to unequal pressure on the aerofoil surfaces facing toward and away from the oncoming flow.

To represent the potential of an airfoil to generate lift and drag forces, the lift coefficient, C_L, and the drag coefficient, C_D, are used. They are defined as follows.

$$C_L = \frac{F_L}{\frac{1}{2}\rho A_{proj} V_{REL}^2} \tag{1}$$

$$C_D = \frac{F_D}{\frac{1}{2}\rho A_{proj} V_{REL}^2} \tag{2}$$

where A_{proj} is the area on the top view of the blade fragment that generates the force in question, that is, the projection area of the blade fragment on the perpendicular plane to the plane of the airfoil and containing the chord. Figure 4 shows the area to be considered in the above expressions for a blade fragment of differential length.

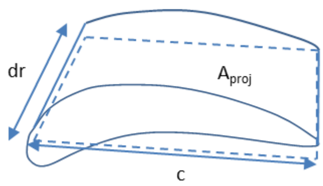

Figure 4. Area on the top view of a differential of the blade

We express the contribution to the support (dF_L) of the blade element of Figure 4 using the lift force per length unit.

$$dF_L = Ldr \tag{3}$$

The area on the top view will also be differential, being obtainable as the product of the chord c by the length dr:

$$dA_{proj} = cdr \tag{4}$$

yielding

$$C_L = \frac{L}{\frac{1}{2}\rho c V_{REL}^2} \tag{5}$$

Doing the same for the drag force, we have,

$$C_D = \frac{D}{\frac{1}{2}\rho c V_{REL}^2} \tag{6}$$

For a given profile, these coefficients are a function of Reynolds number, Re, of Mach number, Ma, of the angle of attack α and of the surface roughness. However, for a wind turbine rotating at moderate speed, the influence of Ma and Re can be neglected without undue loss of precision [9].

There are databases where lift and drag coefficients are tabulated and graphed based on some of the above variables; particularly based on the angle of attack [10]. In some cases data are experimental, profiles having been tested in wind tunnels. In other cases, it comes from predictions or simulations using computational fluid dynamics.

The latter is the case of Figures 5 and 6 [10], representing the coefficients of lift and drag based on the angle of attack for $Re = 1\times10^5$ (orange and green) and $Re = 5\times10^5$ (purple and blue), for different roughness. The profile is the NACA 63-415, recommended for wind turbine blades [9].

We can see that there are certain differences between these curves, as chosen Reynolds numbers are quite dissimilar. Moreover, these occur especially for large values of the angle of attack; although this is an unusual operation zone (this kind of profiles usually works around 4° of α [9] [11]). Changes in roughness also generate some differences.

BEM method uses the lift and drag coefficients of each aerofoil element with the local geometry and design flow conditions to predict aerodynamic performance. To analyze an element, the designer must first determine the section pitch angle θ, local speed ratio λ_r, and lift and drag coefficients C_L and C_D at the local angle of attack α. B is the number of blades, R is the rotor radius, c is chord length at r, and U_{rel} is the relative wind velocity at r.

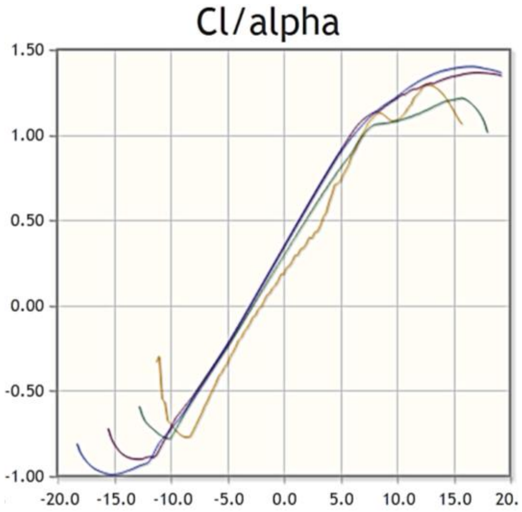

Figure 5. C_L based on α for different *Re* and roughness [10]

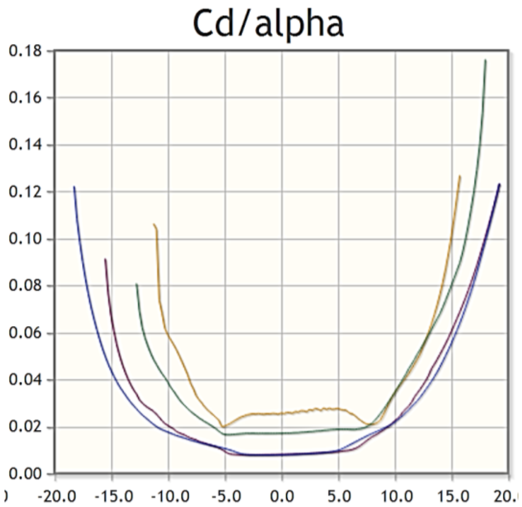

Figure 6. C_D based on α for different *Re* and roughness [10]

The axial induction factor a, tangential induction factor a', and the angle of relative wind ϕ for a single element are [3], [9].

$$a = \frac{1}{\frac{4F\sin^2\phi}{\sigma\left(C_L\cos\phi + C_D\sin\phi\right)} + 1} = \frac{1}{\frac{4F\sin^2\phi}{\sigma C_N} + 1} \tag{7}$$

$$a' = \frac{1}{\frac{4F\sin\phi\cos\phi}{\sigma\left(C_L\sin\phi - C_D\cos\phi\right)} - 1} = \frac{1}{\frac{4F\sin\phi\cos\phi}{\sigma C_T} - 1} \tag{8}$$

$$\phi = \theta + \alpha = \tan^{-1}\left[\frac{1-a}{(1+a')\lambda_r}\right] \tag{9}$$

$$F = F_{hub}F_{tip} = \frac{2}{\pi}\cos^{-1}\left\{\exp\left[-\frac{B(r-R_h)}{2r\sin\phi}\right]\right\}. \\ .\frac{2}{\pi}\cos^{-1}\left\{\exp\left[-\frac{B(1-r/R)}{2(r/R)\sin\phi}\right]\right\} \tag{10}$$

$$\sigma = \frac{Bc}{2\pi r} \tag{11}$$

where F is total loss factor including tip loss and hub loss (F=1 if there are no tip loss F_{tip} or hub loss F_{hub} corrections), R is rotor radius, R_h is the hub radius, and U is the free stream wind speed. These equations are solved iteratively for each element. Equations (7) and (8) are also shown based on normal load coefficient C_N and tangential load coefficient C_T.

To achieve a higher level of accuracy, we would have to consider all these factors; however, it is an additional complication whose advantages are not worthwhile. So the best way to work is to select the profile data that we will use for the values of the Reynolds number and the typical roughness and consider the coefficients of drag and lift as functions of only the angle of attack.

Notice in the above figures that for values of α greater than 15°, C_L stalls while C_D increases. This phenomenon is called stall and occurs due to a process of detachment of the boundary layer that generates turbulence in the flow. The phenomenon is shown in Figure 7, where the value of both coefficients based on α are represented for a NACA 0012 profile [12].

As discussed below, it is common to try to adjust the variables chosen for the aerofoil work in an optimal angle of attack. The latter usually understood as one that maximizes the lift minimizing drag, i.e. maximizing C_L/C_D.

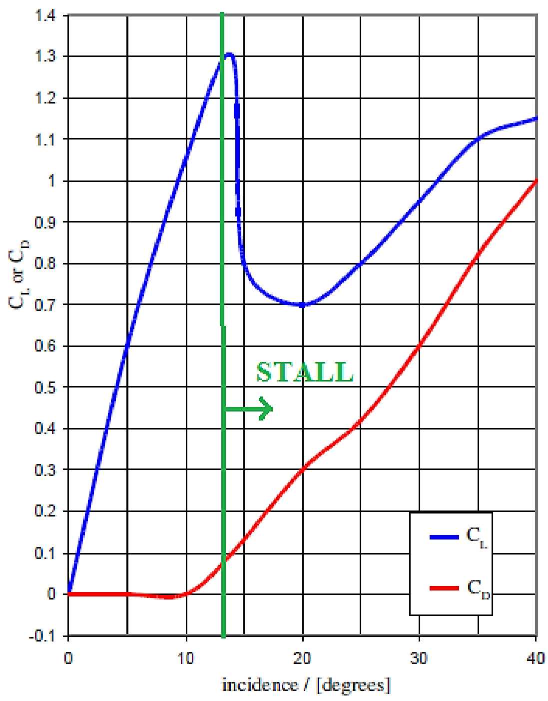

Figure 7. CD and CL as functions of α according to a profile NACA 0012. Stall phenomenon [12]

VI. CONCLUSIONS

Blade design is a very important factor in the performance and therefore in the productivity of a wind turbine. In this paper, we have analyzed the lift and drag coefficients for a blade with NACA profiles. It is common to try to adjust the variables chosen for the aerofoil work in an optimal angle of attack.

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REFERENCES

[1] Asociacion Empresarial Eolica, AEE (Spanish Wind Energy Association), http://www.aeeolica.org/en/new/the-spanish-wind-power-sector-installs-zero-megawatts-in-2015-an-unknown-situation-since-the-80s/, June 2016.

[2] J. Bilbao, E. Bravo, O. Garcia, C. Varela, M. Rodriguez, P. Gonzalez, "Introduction to the Design of the Blades of a Wind Turbine of Low Power and Low Cost", 11th International Conference on Technical and Physical Problems of Electrical Engineering (ICTPE-2015), Bucharest, Romania, 7-9 September 2015.

[3] J.F. Manwell, J.G. McGowan, A.L. Rogers, "Wind Energy Explained: Theory, Design and Application", 2nd Edition, Wiley, New York, NY, USA, 2009.

[4] S.A. Kale, R.N. Varma, "Aerodynamic Design of a Horizontal Axis Micro Wind Turbine Blade Using NACA 4412 Profile", International Journal of Renewable Energy Research, Vol. 4, No. 1, 2014.

[5] G. Ingram, "Wind Energy Blade Analysis Using the Blade Element Momentum Method", Durham University, October 2011.

[6] A. Vardar, B. Eker, "Principle of Rotor Design for Horizontal Axis Wind Turbines", Journal of Applied Sciences, Vol. 6, No. 7, pp. 1527-1533, 2006.

[7] C. Bak, "Sensitivity of Key Parameters in Aerodynamic Wind Turbine Rotor Design on Power and Energy Performance", Journal of Physics, Vol. 75, No. 1, 2007.

[8] J. Bilbao, E. Bravo, O. Garcia, C. Varela, M. Rodriguez, P. Gonzalez, "Blade Aerodynamic Design and Analysis as First Step to Achieve the Expected Power Performance of a Small Wind Turbine", International Journal on Technical and Physical Problems of Engineering (IJTPE), Issue 24, Vol. 7, No. 3, pp. 42-46, September 2015.

[9] M.O.L. Hansen, "Aerodynamics of Wind Turbines", Padstow, UK Earthscan, 2008.

[10] NACA 63-415 Airfoil Details, "Airfoil Tools", http://airfoiltools.com/airfoil/details?airfoil=n63415-il.

[11] H. Piggott, "Windpower Workshop", Machynleth, CAT Publications, 1997.

[12] G. Ingram, "Wind Turbine Blade Analysis Using the Blade Element Momentum Method", Durham University, 2011.

BIOGRAPHIES

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