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DESIGNING AND PROJECTING A WIND GENERATOR BASED ON THE EMPLACEMENT: POWER COEFFICIENT

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Abstract- In the field of electricity generation, wind energy is currently the main source of renewable energy in many countries of the world. The amount of energy generated in this way has been increasing in recent years, reaching levels similar to, or even higher than, other types of energy, depending on each country. This strong increase in wind energy generation is causing, in certain countries, a problem in the location of new wind farms. There are various factors, such as proximity to urban centers, environmental protection, etc., but in any case, there is an effect whereby the development of marine wind energy is increasing. One of the consequences of this problem is that the optimization of the aerodynamic efficiency of wind turbines should be necessary in wind energy generation projects. This may involve, on the one hand, the better qualification of sites and their generation potential and, on the other hand, the possibility of being able to start with the replacement of old turbines with better performance ones. This article introduces the concept of wind turbine aerodynamic efficiency for possible modelling and optimization in wind energy projects.

Keywords: Wind Turbine, Wind Energy, Power Coefficient, Emplacement.

1. INTRODUCTION

Nowadays, energy is considered a necessary good for almost any daily activity, but it is essential in any industrial process. Moreover, energy is today a key factor in economic development. Among the many existing energy sources, renewable energy resources have recently received much attention due to several factors, including the disadvantages of overuse of expensive non-renewable fossil fuels, such as environmental pollution caused by the production of harmful gases (e.g. carbon monoxide and Sulphur oxide) and greenhouse gases (carbon dioxide and methane) [1-4].

In just one decade, wind energy has been climbing positions in the ranking of the European energy mix, becoming in 2016 the second source of energy generation in Europe, only behind gas plants [5].

The wind potential available at a site depends on various aspects, including the permanence of atmospheric conditions with high wind speeds associated with the topography, the roughness of the land surrounding the site, the thermodynamic conditions of the atmosphere and the altitude above sea level. These different determinants determine the most significant meteorological factors from an energy point of view, such as wind speed and direction, turbulence levels and scales, and atmospheric temperature and pressure [6].

The available power flow, P in watts, in the moving air masses with respect to the earth's surface is expressed according to Equation (1) as:

$$P = \frac{1}{2}\rho A v^3 \tag{1}$$

In the Equation (1), ρ is the air density (kg/m^3), A is the surface area (m^2), which the airflow passes through, and v is the average wind speed (m/s).

In this way, the atmospheric flow is turbulent. The intensity of turbulence and the scales of the turbulence depend mainly on the roughness of the terrain, the existing obstacles and the thermodynamic state of the atmosphere. As the roughness of the terrain increases, the intensity of the bursts generally also increases and the scale of the temporal variation of the bursts increases. For this reason, on the sea the wind is, in general, less turbulent and has large scales, while on land the turbulence is greater and the scale of variations is smaller. The variations that the wind undergoes in time associated with the turbulence can present characteristic times in an interval from 3 seconds to 10 minutes, in the majority of the cases.

To evaluate the effectiveness of a wind turbine installed in a given site in order to convert wind energy into electrical energy, the capacity factor parameter is usually used. This parameter is defined as the rate between the average power that the wind turbine would generate, if installed at the given site, and the nominal power of the equipment.

Another way in which this parameter is usually expressed is as the number of hours that the wind turbine should work at nominal power, to generate the amount of energy if it had been installed at the given site. It should be emphasized that with the help of this parameter, it would be possible to evaluate the way in which different wind turbines would operate in the same site.

But obviously, another important factor that must always be considered is the wind turbine itself: its design, height, aerodynamic profile of the blades, etc.

2. PRELIMINARY ANALYSIS FOR A WIND TURBINE AND ITS EMPLACEMENT

The source of wind energy is the movement of the air: the wind, which is originated by the unequal heating of the surface of our planet, forming movements of the atmospheric mass. It is not a new source of energy, but what has changed in the use of wind power in the last decades is the technology used, the new materials, the search for appropriate locations for wind farms, etc. Nowadays, efforts are being made to develop solutions that allow better use to be made of this type of installation [7]. These efforts must take into account the estimation, evaluation and exploitation of the wind resource.

The use of mathematical models to determine the wind potential of a region includes previous studies to monitor the speed, direction, density and temperature of the site, and an adequate handling of data in order to develop the tools that determine the potential [8].

Wind speed profiles, wind roses and wind maps of an area, for an established period of time, provide the guidelines to see the feasibility of taking advantage of the existing wind resource, through the installation of wind turbines.

For preliminary estimates, maps can be drawn up based on observation of nature, that is, visual inspection of indicators or physical evidence, as well as surveys of the inhabitants. The indicators to be taken into account are mainly two, according to [9]:

- Geological indicators, such as wind erosion on a hill or rugged coastline. They can show that for centuries erosion caused by wind that was "working" in a particular direction [9].
- The ecological indicators of wind, the most notable of which are those provided by vegetation. Trees and shrubs deformed by the action of the wind are very valuable records of the speed and direction of the dominant wind. Nature shows how to estimate wind speed from the deformation of tree and shrub foliage according to highly visible ecological indicators [9].

Once the physical evidence has been analyzed, it is necessary to obtain the following data as accurately as possible:

1. Wind data. Speed, direction, temperature and height at which the measurements of these parameters were made.
2. Site data. Height above sea level, geographical coordinates, location maps, topographical map of contour lines in printed and electronic format. It is also necessary to have, whenever possible, photographs of the place where the monitoring station is installed and its surroundings, as well as an aerospace view.

The methodology for data evaluation consists of five main steps:

- Obtaining the wind data previously mentioned.
- Mathematical evaluation of the site, by extrapolating wind speeds at different heights to those at which the records were taken.
- Obtaining average wind speeds, wind roses, power density, by means of data bases and/or specialized software.
- Calculation of monthly, seasonal or annual energy production.
- Analysis of graphs and maps.

With the wind and site data, a wind map can be produced based on simulation methods using appropriate software, which, together with the map of geological and ecological wind indicators, can help to locate promising areas. However, only measurements at the wind site, at heights close to the wind turbine hub, for at least one year, can determine the exact location, that is, the optimum micro-location of the wind farm.

3. POWER COEFFICIENT OF A WIND TURBINE

Determining the wind potential in a site or area involves characterizing the wind climate in that location. Usually, with rare exceptions, no meteorological information is available at the appropriate sites to exploit the wind resource. For this reason, a series of methodologies emerge to characterize the wind climate at the site. These methodologies include on-site measurement, the so-called Wind Atlas methodology, the application of numerical models, the application of physical models, or the joint application of both [10].

Among the measurement methodologies, one could discriminate between short- and long-term measurements. The short duration measurement is made over a period of enough time to characterize the different atmospheric patterns recorded at the site. Then, from this measurement, correlating it with available meteorological information of long duration, obtained from a nearby meteorological station, historical series of wind are deduced that allow a feasibility study of wind energy use to be carried out.

Long-term measurements refer to measurements taken over at least one year. The selection of the type of anemometer and its location, as well as the measurement strategy will depend mainly on the characteristics of the terrain, the stage of the wind potential study and the dimensions of the wind turbines to be installed.

When characterizing the wind potential in flat areas, the use of low height masts is feasible because in a simple and reliable manner the speed at the desired height can be deduced by applying empirical models of the analytical type. If the terrain presents a complex topography, then the measurement should be carried out at a height similar to that of the wind turbines to be installed and a certain number of measurement sites should be available, the more complex the terrain. The latter seeks to identify peculiar behavior resulting from the interaction between topography and wind. This wind climate characterization methodology is interesting to apply in advanced stages of wind potential assessment or in cases of analysis of specific sites, or when wind exploitation is in operation [11].

The methodology called Wind Atlas is based on the availability of very high quality measurements that allow the wind to be accurately deduced at geostrophic height (upper edge of the atmospheric boundary layer) using information on the type of surrounding terrain. Then, from the application of the constant geostrophic law and the knowledge of the terrain at the site of interest, the wind speed at the desired height is deduced. The application of this methodology presents strong restrictions in areas of complex topographies, in areas where there are highly stable or unstable thermodynamic states of the atmosphere and where data of due quality is not available [12].

Numerical methodologies include the application of mass conservation models, particular flow solutions in special situations and the modelling of turbulent flows. As the topography becomes more complex, it becomes difficult to apply the approximate methodologies and the computer requirements to perform the calculation increase.

Physical modelling allows the description of the flow around areas of complex topography, but it requires field data that allows the deduction of speed values in the sites that are analyzed, since in the physical model only relative values can be deduced, referring to reference velocity values [13-15].

With respect to other type of modelization, such as the nested techniques, different tools are used that allow the flow to be resolved at different scales. As an example, a numerical mass conservation model allows the flow to be resolved at the mesoscale of meteorology, while a physical model does so at the micro-scale of meteorology. Then, the numerical model is first run and its output is used as a boundary condition of the physical model. The advantage of this methodology is that, in addition to describing the flow through both average and fluctuating values, it makes it possible to cover large areas without having to take measurements.

The wind potential available at a site depends on various aspects, among which the permanence of atmospheric states with associated high wind speeds, the topography, the roughness of the land surrounding the site, the thermodynamic states of the atmosphere and the altitude above sea level stand out [16]

These different determinants define the most significant meteorological factors from the energy point of view, such as wind speed and direction, turbulence levels and scales, and atmospheric temperature and pressure [11].

The kinetic energy of a m mass or object in motion, and with a v speed is described by:

$$E = \frac{1}{2} m v^2 \quad (2)$$

Then, being the power the energy per unit time t, it will be had:

$$P = \frac{E}{t} = \frac{1}{2} m \frac{v^2}{t} \quad (3)$$

But it should also be considered that the density of matter, ρ, is given by the mass between its volume V, that is:

$$\rho = \frac{m}{V} \quad (4)$$

Solving the mass, we have:

$$m = \rho V \quad (5)$$

The volume can also be interpreted as an area A per unit length l,

$$V = Al \quad (6)$$

Then, substituting Equations (4), (5) and (6) into Equation (2) will be obtained:

$$P = \frac{1}{2} \rho A \frac{l}{t} v^2 \quad (7)$$

But a distance travelled in a time represents a speed ($v = l/t$), therefore:

$$P = \frac{1}{2} \rho A v v^2 = \frac{1}{2} \rho A v^3 \quad (8)$$

The available power flow in the moving air masses with respect to the earth's surface is expressed according to Equation (1).

The determination of atmospheric density basically implies knowing the ambient temperature and pressure, assuming that air behaves like a perfect gas. In Table 1, we can find the values of dry air density at a pressure of 1 atm for different temperatures, as well as other variables that may be of interest in the calculations.

Table 1. values of dry air density at a pressure of 1 atm

T °C	ρ kg/m³	c_p kJ/kg·K	$\mu \cdot 10^6$ N·s/m²	$\nu \cdot 10^6$ m²/s	$k \cdot 10^3$ W/m·K	$\alpha \cdot 10^6$ m²/s
-50	1.582	0.999	14.74	9.317	19.79	12.52
-40	1.514	1.002	15.27	10.08	20.57	13.56
-30	1.452	1.004	15.79	10.88	21.34	14.65
-20	1.394	1.005	16.30	11.69	22.11	15.78
-10	1.341	1.006	16.80	12.52	22.88	16.96
0	1.292	1.006	17.29	13.38	23.64	18.17
5	1.269	1.006	17.54	13.82	24.01	18.80
10	1.247	1.006	17.78	14.26	24.39	19.44
15	1.225	1.007	18.02	14.71	24.76	20.08
20	1.204	1.007	18.25	15.16	25.14	20.74
25	1.184	1.007	18.49	15.61	25.51	21.40
30	1.164	1.007	18.72	16.08	25.88	22.08
35	1.146	1.007	18.95	16.54	26.25	22.76
40	1.117	1.007	19.18	17.02	26.62	23.45
45	1.110	1.007	19.41	17.49	26.99	24.16
50	1.092	1.007	19.63	17.97	27.35	24.87

The most relevant magnitude in the characterization of the wind resource in a site is the average wind speed. This parameter can present important temporal and spatial variations.

Temporal variations present different scales depending on the type of meteorological factor with which they are associated.

From Equation (1) the power density can be expressed by Equation (1) as $P = \frac{1}{2} \rho A v^3$.

Applied to the power that can be obtained from an air flow that affects a specific circular area A and with a diameter D in meter ($A = \pi D^2/4$), it has to be:

$$P = \frac{1}{2} \rho A v^3 = \frac{1}{2} \rho \pi \frac{D^2}{4} v^3 \quad (9)$$

where, in this case, ρ is the density of the air at the point to be treated, whose value, for example, is 1.225 kg/m^3 at 15 °C and a pressure of 1 atm [17].

For heights different from sea level, the density can be calculated by the equation:

$$\rho = \frac{pM}{RT} \quad (10)$$

where, p is the absolute pressure of the atmosphere, M is molar mass of the dry air (0.0289644 kg/mol), R is the universal or ideal gas constant, 8.31447 J/(mol·K), and T is the temperature, in Kelvin.

3.1. Power Coefficient of a Wind Turbine

The power coefficient of a wind turbine is one of the main factors to take into account when you design and project a wind generator and when you want to install it in a analyzed place. One the methods that we can use to determine a functional relationship of the wind turbine power coefficient $C_p = f(\lambda,\sigma,\theta)$ is the model of the minimum deviation (MMD). It is necessary to obtain information about the power coefficient of wind turbines with known characteristics $C_p = f(\lambda,\sigma,\theta)$, which is obtained for profiles of the type NACA or other.

Normally, the geometric and operating variables are:
- Passage angle (θ)
- Profile strength (σ)
- Speed Ratio (λ)

The modeling is done by the model of the minimum deviation (MMD), which is developed to obtain a simplified mathematical model for the calculation of the power coefficient $C_p = f(\lambda,\sigma,\theta)$.

In this process, the main objective is to find some parameters so that the sum of the deviations is minimal, taking into account f and F functions:

$$\sum_{j=1}^{n}\left[f(\lambda,\sigma,\theta) - F(\lambda,\sigma,\theta)\right]^2 \quad (11)$$

where, n is the amount of aerodynamic efficiency considered data in the process

Since it is desired to obtain the sum of the deviations to be minimal, the D function is defined according to Equation (12).

$$D = \sum_{j=1}^{n}\left[f(\lambda_j,\sigma_j,\theta_j) - F(\lambda_j,\sigma_j,\theta_j)\right]^2 \quad (12)$$

Equation (13) represents the functional formulation.

$$F(\lambda_j,\sigma_j,\theta_j) = \sum_{j=1}^{k} a_j \cdot x_j \quad (13)$$

where, k is the number of coefficients, and x_j is the function defined as a combination of the parameters $(\lambda_j,\sigma_j,\theta_j)$.

Deriving the Equation (12) with respect to the coefficients a_j, we obtain:

$$\frac{\partial D}{\partial a_j} = -2\sum_{j=1}^{n}\left\{\left[f(\lambda_j,\sigma_j,\theta_j) - F(\lambda_j,\sigma_j,\theta_j)\right]\cdot \frac{\partial F(\lambda_j,\sigma_j,\theta_j)}{\partial a_j}\right\} \quad (14)$$

Being our objective to obtain an extreme, we have to do:

$$\frac{\partial D}{\partial a_j} = 0 \quad (15)$$

Then the Equation (14) results:

$$\sum_{j=1}^{n}\left\{\left[f(\lambda_j,\sigma_j,\theta_j) - F(\lambda_j,\sigma_j,\theta_j)\right]\cdot \frac{\partial F(\lambda_j,\sigma_j,\theta_j)}{\partial a_j}\right\} = 0$$

(16)

From the Equation (13), we will obtain that:

$$\frac{\partial F(\lambda_j,\sigma_j,\theta_j)}{\partial a_j} = \frac{\partial}{\partial a_j}\sum_{j=1}^{k} a_j \cdot x_j = x_j \quad (17)$$

For this development, we will assume that $k = n$.

Replacing the Equation (13) and the Equation (17) in the Equation (16), we obtain:

$$\sum_{j=1}^{n}\left\{\left[f(\lambda_j,\sigma_j,\theta_j) - \sum_{j=1}^{n}\left(a_j \cdot x_j\right)\right]\cdot x_j\right\} = 0 \quad (18)$$

And from this last equation, we can obtain the Equation (19), which is represented as a generalized system of equations, for n unknowns, a_1, a_2, … , a_n.

$$\sum_{j=1}^{n}\left[\left(a_j \cdot x_j\right)\cdot x_j\right] - \sum_{j=1}^{n}\left[f(\lambda_j,\sigma_j,\theta_j)\cdot x_j\right] = 0 \quad (19)$$

With simple operation:

$$\sum_{j=1}^{n}\left(a_j \cdot x_j\right)\cdot x_j = \sum_{j=1}^{n} f(\lambda_j,\sigma_j,\theta_j)\cdot x_j \quad (20)$$

Generalizing the equations, and considering only the development for the x functions, we will obtain the system, written in matrix form in the Equation (21).

$$\begin{bmatrix} x_1\cdot x_1 & x_2\cdot x_1 & x_3\cdot x_1 & \cdots & x_{n-1}\cdot x_1 & x_n\cdot x_1 \\ x_1\cdot x_2 & x_2\cdot x_2 & x_3\cdot x_2 & \cdots & x_{n-1}\cdot x_2 & x_n\cdot x_2 \\ x_1\cdot x_3 & x_2\cdot x_3 & x_3\cdot x_3 & \cdots & x_{n-1}\cdot x_3 & x_n\cdot x_3 \\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\ x_1\cdot x_{n-1} & x_2\cdot x_{n-1} & x_3\cdot x_{n-1} & \cdots & x_{n-1}\cdot x_{n-1} & x_n\cdot x_{n-1} \\ x_1\cdot x_n & x_2\cdot x_n & x_3\cdot x_n & \cdots & x_{n-1}\cdot x_n & x_n\cdot x_n \end{bmatrix} \cdot \begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ \vdots \\ a_{n-1} \\ a_n \end{bmatrix} = \begin{bmatrix} f(\lambda_1,\sigma_1,\theta_1)\cdot x_1 \\ f(\lambda_2,\sigma_2,\theta_2)\cdot x_2 \\ f(\lambda_3,\sigma_3,\theta_3)\cdot x_3 \\ \vdots \\ f(\lambda_{n-1},\sigma_{n-1},\theta_{n-1})\cdot x_{n-1} \\ f(\lambda_n,\sigma_n,\theta_n)\cdot x_n \end{bmatrix} \quad (21)$$

Therefore, the functional equation of aerodynamic efficiency can be represented as:

$$F(\lambda,\sigma,\theta) = \sum_{i=0}^{3} f_i(\sigma,\theta)\cdot\lambda^i = $$
$$= f_0(\sigma,\theta)\cdot\lambda^0 + f_1(\sigma,\theta)\cdot\lambda^1 + \quad (22)$$
$$+ f_2(\sigma,\theta)\cdot\lambda^2 + f_3(\sigma,\theta)\cdot\lambda^3$$

Then, the equation (23) calculates the aerodynamic efficiency of wind turbines by the model of the minimum deviation:

$$F(\lambda,\sigma,\theta) = C_{p_{MMD}}(\lambda,\sigma,\theta) = \sum_{i=0}^{3} f_i(\sigma,\theta)\cdot\lambda^i \quad (23)$$

4. CONCLUSIONS

By 2016, wind energy is already the second most important energy source in Europe. The installation of new wind turbines continues to increase year after year and it does not seem that this trend will diminish in the near future. Furthermore, old turbines must be replaced by more modern ones and even more powerful ones, as far as possible and depending on several factors. New emplacements should be studied beforehand, not only from the ecological and urban/rural management point of view, but also from the point of view of better use of the wind. Taking into account all these factors, it is important to study the aerodynamic efficiency of wind turbines, this article being an introduction to such a study.

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