

Modeling and Simulation of the Energy Conversion System of a Wind Turbine

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Abstract-- In this paper we propose a new study for modeling and simulation the performance of (Bornay3000) wind turbine implemented in the hybrid system on the site of Laboratory of Research Applied to Renewable Energy (LRAER). It gives also, estimation and evaluation of the production which encompasses performance of the energy conversion system of a wind turbine. To analyze the influence of the interference factor on energy production, our simulations are realized in Matlab environment. The results of this work provide a previous estimation about the suitability between the specific wind turbine type and the installation site.

Index Term-- Wind turbine, Bornay 3000, efficiency, Axial force, Hybrid system.

1. INTRODUCTION

Today, renewable energies have become a focus for the world, given that they are clean and sustainable. This interest is encouraged through wholesale funding for the scientific research in this field. In general, the place of proliferation for longer wind turbines corresponds to coastal areas. Within this framework, the zones of the Atlantic littoral Mauritanian, this has over six hundred kilometers of potential use for wind energy.

In this paper, we present an approach of calculation of the blades for the aerogenerator, which has two blades with a horizontal axis. The developed mathematical models are based on the Betz theory, this method is used to extract the maximum power of energy within the wind speed's intervals. They are recorded on LRAER or Bornay3000, which corresponds to the curve of power of the aerogenerator. In order to extract the maximum power, we must pay special attention to the element that contributes in optimizing wind energy. This element is the wind turbine blade. The size of wind turbine blades varies from one to another. Manufacturers must consider the target performance of their design, so that they can capture as much wind force as possible within security regulations. Every detail counts: the size, number of blades through their attachment to combine several quality aerodynamics, as well

as the lightness, allows for them to achieve the perfected system balance.

Therefore, the goal of our study is to determine the performance of the wind turbine (Bornay 3000) with two blades in the hybrid system LRAER.

We have adopted a voluntary mathematical modeling approach, to highlight the performance of this machine. These performances can be obtained by calculating the aerodynamic forces exerted on the blades of the machine to produce an optimized output power.

In the end, thanks to the mathematical models that have been created[1-3], we can show by simulation on Matlab the performances of the aerogenerator, in the form of various curves.

2. EXPERIMENTAL DEVICE

The experimental device existing at laboratory (LRAER) of Faculty of Sciences And Technology USTM of Nouakchott is an autonomous system, composed of a hybrid system of electrical production (wind turbine-photovoltaic-diesel) with 5.7 KW connected to a water desalination unit (osmosis reverses) along with other loads and secondary equipments (Figure 1)[4,5].

Producing electric chain hybrid system consists of following elements:

Two aerogenerators: 1.5 kW and 3 kW Bornay mark, related to the continuous bus via a diode Inverted.

16 photovoltaic panels (1.2 kW) connected to the continuous bus.

A generator of 5 kW nominal power.

The energy storage device implanted in this hybrid system is connected directly to the continuous bus.

The last is connected to the alternative network via a reversible inverter (4.5 kW, of brand Trace Engineering, SW)



Fig. 1. Experimental device (LRAER)

3. GEOMETRICAL CHARACTERISTICS OF BORNAY3000

The knowledge of the geometrical characteristics of Bornay and the blades profile (Figure 2), allow for optimal energy conversion. It also allows for a better return on the aerodynamic forces. We are particularly interested in the

compartments in this blade, which is a twin-bladed propeller ($n = 2$) - subjected to different simulated wind speed at our site.

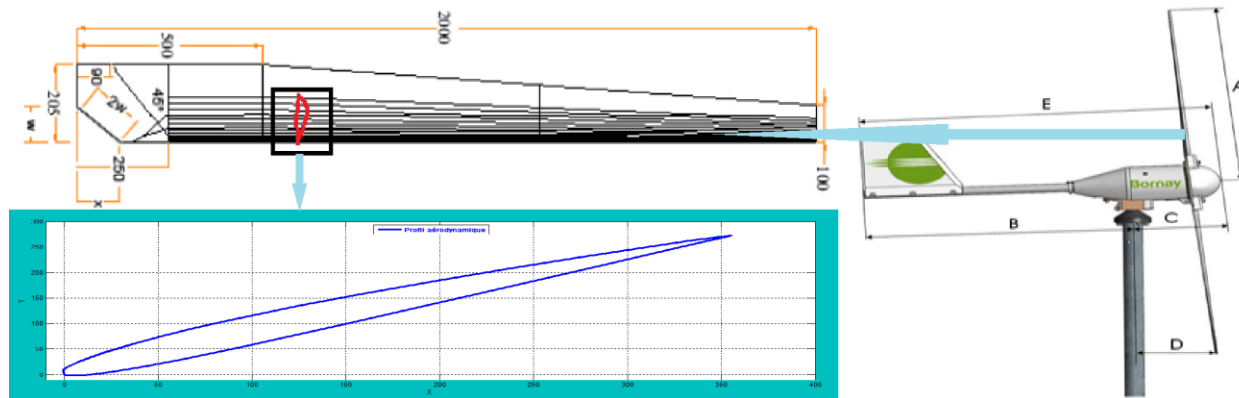


Fig. 2. Airfoil of the wind turbine blade (Bornay 3000) on Matlab

The table below gives the characteristics of the airfoil for four types of Bornay wind turbines, including Bornay3000[6]. However, we acknowledge the representation of the aerodynamic profile of the wind turbine Bornay3000 blade by Matlab. The simulation is based on the data of the machine profile.

Module	A (mm)	B (mm)	C (mm)	D (mm)	E (mm)
Bornay600	1000	1120	350	360	1470
Bornay1500	1430	1670	370	470	2040
Bornay3000	2000	2140	470	645	2610
Bornay6000	2000	2640	495	645	3135

It is important to note that our blade profile is provided by Matlab. It is done with two parameters (X, Y), which summarize the characteristics of the aerodynamic profile of

the blades of the wind turbine (Bornay3000). This method of approximation of the profile is achieved with Bornay3000, which can serve for testing of optimization of the characteristics of this type of machine through different profiles of the blades in search of an optimization by Matlab tool.

4. MODELING

Regarding this part related to modeling of flows of fluids and in accordance with what is stated above, the general theory of the wind engine (turbine) with a horizontal axis has been established by Betz under the hypotheses following:

- Axial flow (air movement is not rotating)
- Incompressible flow,
- Air passing through the rotor without friction,

$$P_1 = P_4 \text{ et } V_2 = V_3 \quad (1)$$

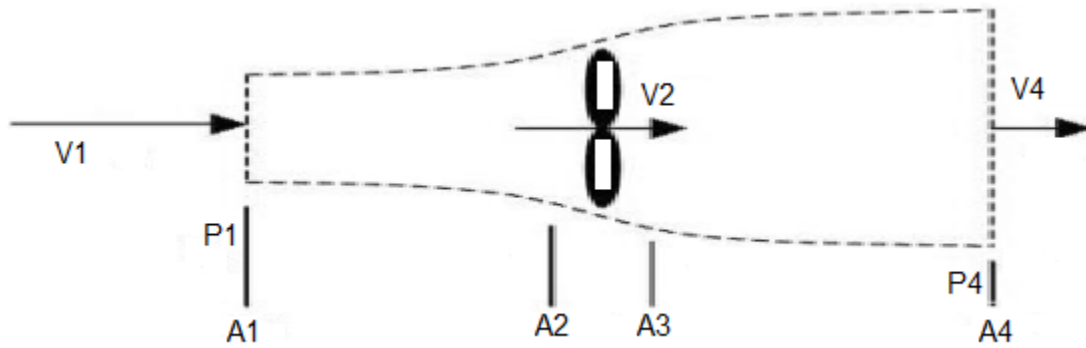


Fig. 3. Axial flow of the air

This theory is based on the following principles:

- The principle of conservation of mass

$$S_1 V_1 = S_2 V_2 = S_3 V_3 = S_4 V_4 \quad (2)$$

- Bernoulli's equation

$$\frac{1}{2} \rho V^2 + P + \rho g z = cste \quad (3)$$

Applying Bernoulli's equation on the stations 1 and 2 (Figure 3) gives:

:

$$P_2 - P_3 = \frac{1}{2} \rho (V_1^2 - V_4^2) \quad (4)$$

$$F_x = \Delta P S = \frac{1}{2} \rho S (V_1^2 - V_4^2) \quad (5)$$

Since, $V_2 < V_1$ then we have:

$$V_2 = V_1 (1-a) \quad (6)$$

Principle of change of momentum (from V of the air wind between upstream and downstream of the propeller) allows us to write the relations of force and mechanical power exerted on the blade:

$$\sum F_{ext} = m \Delta V = m (V_1 - V_4) \quad (7)$$

$$F_x = \rho V_2 S (V_1 - V_4) \quad (8)$$

The equality of the two equations (5) and (8) gives the following expression:

$$V_2 = \frac{V_1 + V_4}{2} \text{ et } V_4 = V_1 (1-2a) \quad (9)$$

Introducing the equation (9) in expression (8), we have the equation as follows in axial force:

$$F_x = 2a(1-a) \rho V_1^2 \pi r^2 \quad (10)$$

Mechanical power is expressed as the equation:

$$P_r = F V_2 = \rho S V_2^2 (V_1 - V_4) \quad (11)$$

Next, we introduce the equations (9) and (10) into equation (11), to find equation (12):

$$P_{extr} = \frac{1}{2} \rho \pi r^2 V_1^3 4a(1-a)^2 \quad (12)$$

The power available from the wind depends on the area swept by the propeller of the wind wheel, the density of air and the wind velocity. We can express it as:

$$P_{disp} = \frac{1}{2} \rho \pi r^2 V_1^3 \quad (13)$$

We obtain C_p depending on interference factor, hence, the following equation, which characterizes the efficiency and performance of the wind turbine, in the equation:

$$C_p = \frac{P_{extr}}{P_{disp}} = 4a(1-a)^2 \quad (14)$$

The maximum value of the power coefficient (Betz limit) can be obtained by differentiating equation (14) and equating to zero, to obtain the equation (15):

$$\frac{dC_p}{da} = 0 \Rightarrow a = \frac{1}{3} \quad (15)$$

Under these conditions the power is maximum; it is given in the form of (16):

$$P_{max} = \frac{16}{27} \frac{1}{2} \rho S V_1^3 \quad (16)$$

Thus we get the Betz limit (C_p) in the equation (17) as:

$$C_p = \frac{16}{27} 100 = 4a(1-a)^2 \approx 59.26\% \quad (17)$$

According to the theory of Betz, an aerodynamic performance of a wind turbine may not be higher than 59.26% (Betz limit). In practice, it has a yield of 50% in relation to the last wind turbines manufactured in Europe along with the minimum flow of interference through the blades.

5. SIMULATIONS

Figure 4 shows the situation that characterizes the movement of the wind in the LRAER site at the height of 11 m. This figure allows us how to define the basic conditions of our simulation on Matlab. The range of the wind speed is between 1.5m / s and 9 m / s with an average speed equal to 4.3m / s and $\rho = 1.146 \text{ kg / m}^3$ is the air density of dry air (at a temperature equal to 35 ° C and an atmospheric pressure equal to 1020 hPa).

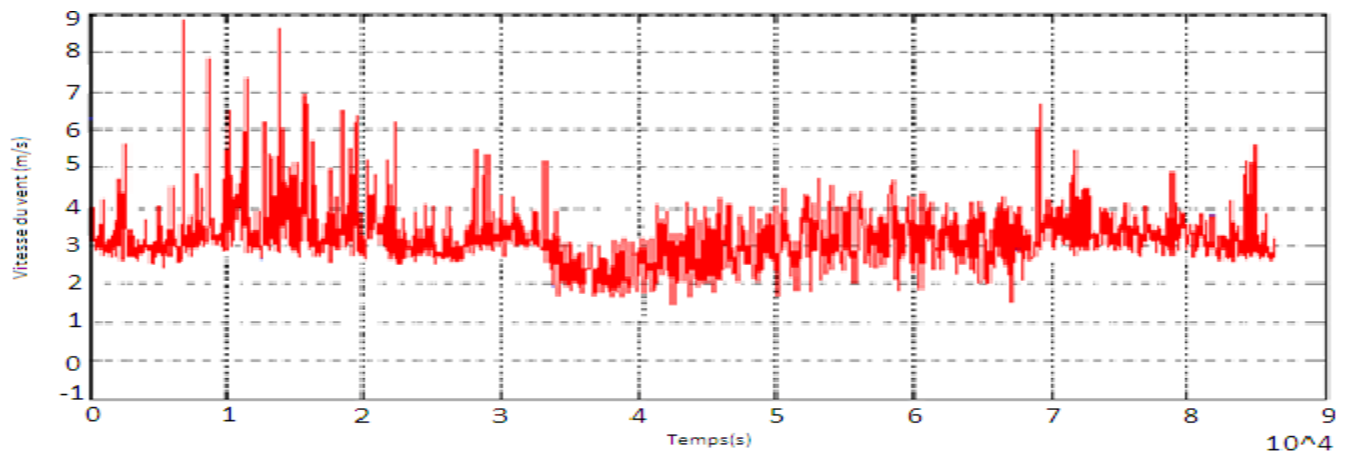


Fig. 4. Real speed of the wind on the site (LRAER)

Before starting the simulations, it is important to include in this part, the two parameters used in the mathematical model of the axial force (équation.10), these include the radius (R) and distribution of wind speed (V). These two parameters will be subjected to variations as a function of a (interfering factor). So it is important to know why the choice of their execution intervals for simulation.

For the first parameter, the manufacturer Bornay gives a wind speed in the interval of 2 to 20 m / s (Figure 5), wherein the average speed of the site is close to 4.3 m / s. The

manufacturer provides for a wind turbine power curves (see Figure 5), the minimum starting speed is 2 m / s and maximum speed as 25 m / s. These values correspond to modern wind turbines of small powers in the lower power range of 10 kilowatts (will not exceed 100). The gusts (Figure 4) given by the wind speed on the site (speed peaks for a very limited period of time) can reach 9 m / s. Then we will run the simulation, taking into account variations in the wind speed of the wind generator curve in the range of speeds recorded in LRAER [1-9 m / s] and an average fixed speed around 4.3 m / sec, given by the same data acquisition system.

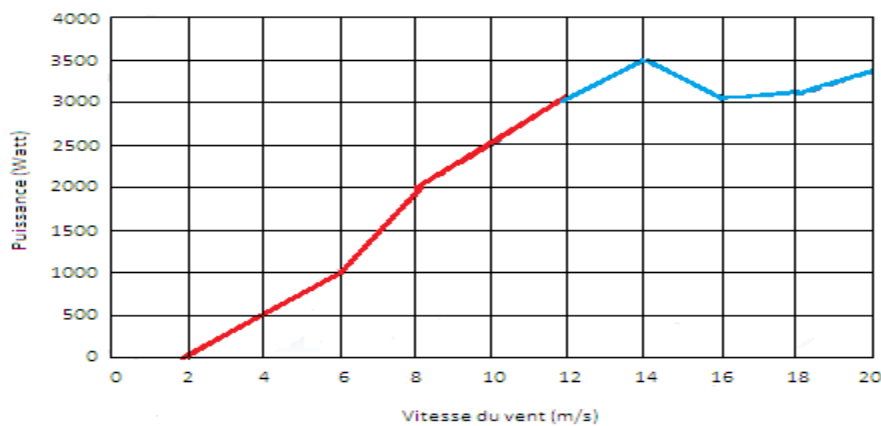


Fig. 5. Curve of power for bornay3000

For the second parameter the radius of the blades is a substantial part of the wind wheel device. The yield of the proper function and machine life depends on its design. The radius of the blades given by the manufacturers of wind motors ranges from 1 m for the small wind turbine to over 2 m from the largest. Wind turbine generator rays can (in case the average power range) run around 275 Kw, reaching over 16m [example in Nouadhibou, Mauritania, we have Vergnet brand wind turbines (75 and 275 Kw)].

It should be noted that for a given wind speed, the power of the turbine proportional to the cube of the speed, as well as the power extracted by the wind turbine through the area swept by the blade, is proportional to the square of length of the

blade. The two parameters (V and R) interest us based on the modeled aerodynamic force in the axial interference factor (a). We are particularly interested in the influence of the two parameters through mathematical models.

5.1 Simulation Aerodynamic Force Based on the Interference Factor.

For this part, the simulations are performed using the following methodology:

- First, we set the radius value ($R = 2\text{m}$) and we change axial force according to (a) with wind velocity (V), for a value of 1 to 9 m / s (Figure 6),
- Next we set the wind speed ($V_m = 4.3\text{ m / s}$, given by the LRAER site), varying we change axial force as a function of (a) with the radius of the blade (R) of 1 to 16 m (Figure 7).
- Finally we give the axial force as a function of (a) with fixed radius ($R = 2\text{m}$) and a fixed average speed ($V = 4.3\text{ m / s}$) (Figure 8)

Axial force according to $V = [1: 9\text{ m / s}]$ $R = 2\text{m}$ (constant)

The axial force gives several variations of the curves as a function of the interference factor. It follows exponential growth. We record each given wind speed in the range $[1: 9\text{ m / s}]$ and an axial force, which takes the magnitude of (5N and 450N).

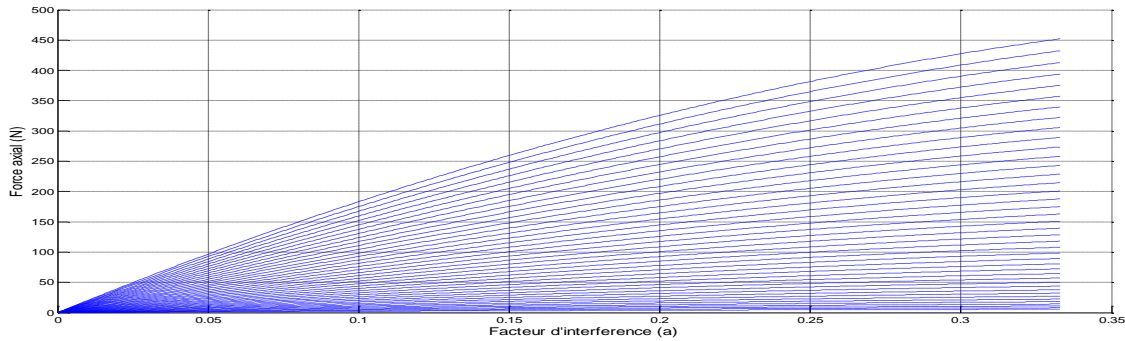


Fig. 6. Axial force in terms of a fixed radius ($R = 2\text{m}$) and velocity distribution $V = [1: 9\text{ m / s}]$

Figure 6 shows that the maximum is obtained by an interference factor of 0.333. The evolution curves quasi are identical in shape but have various values in amplitudes. They respond to the same points on the interference factor.

Physically this phenomenon can be translated as follows: for a given site and for our type of wind turbine; the maximum value of the axial force can be searched around the point of the interference factor of a value close to 0.333. So the wind speed plays a crucial role in the evolution of the axial force.

The axial force is responsive to changes in the curves as a function of the interference factor, following any increase in the radius of the blades. It follows an increasing exponential shape with a maximum limit of around 6500N with a value of (a), close to 0.333. Then for each increasing radius value, we have a maximum corresponding to a maximum value of force at that point (a), close to 0.333. The axial force varies from 0 up to about 6500 N.

Axial force as a function of $R = [1: 16\text{ m}]$ with ($V_m = 4.3\text{ m / s}$) (constant)

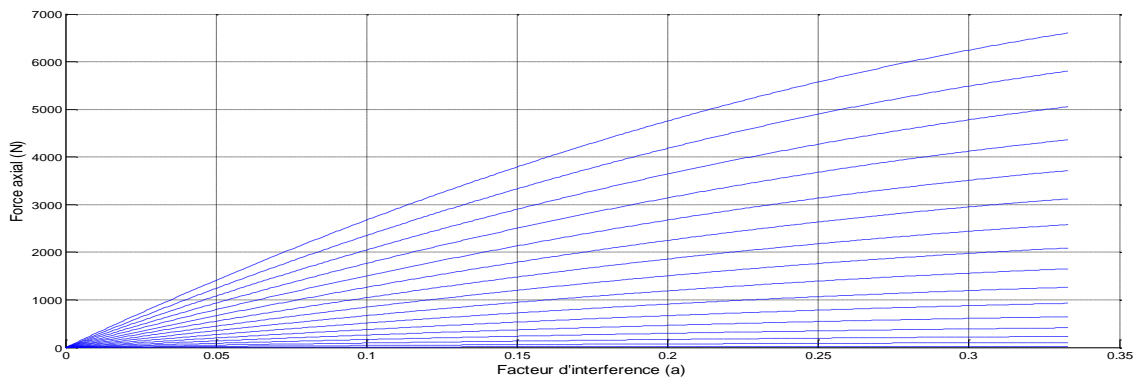


Fig. 7. axial force with a function of a fixed wind speed ($V_m = 4.3\text{ m / s}$) and a blade radius distribution of $R = [1: 16\text{ m}]$

The maximums are registered with an interference factor of 0.333. The evolution curves are Quasi identical in shape but of different values and amplitudes. They respond to the same interference factor points, which are recorded for maximum axial force.

Physically this phenomenon can be translated as follows: for a

given site and for a type of wind turbine, the maximum value of the axial force can be found at the point of the interference factor (0.333). The blades of the radius play a key role in the evolution of the axial force.

Axial force as a function of $R = [2\text{ m}]$ with ($V_m = 4.3\text{ m / s}$)

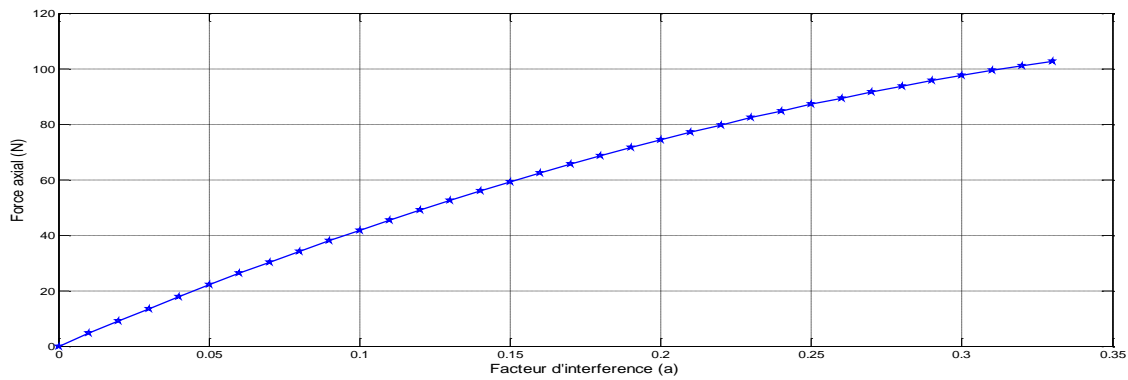


Fig. 8. axial force with a function of a radius ($R = 2$ m) and speed $V = 4.3$ m / s

Analysis of Figure 8 corresponds to the simulation of the equation (10). This shows that the aerodynamic force versus interference factor reaches a maximum value of 100N ($a = 0.333$). It maintains the same growth pattern as previous curves.

5.2 Simulating the Power of Wind Generators Based on the Interference Factor

For this part, the simulations are performed in the form of powers:

- Power of the wind turbine as a function of (a) with a fixed radius and variable speed ranging from [1-9 m / s] (Figure 9),
- Power of the wind turbine as a function of (a) with a fixed wind speed ($V_m = 4.3$ m / s), by varying the radius of the blade (R) from 1 to 16 m (Figure 10),
- The power of the wind turbine as a function of (a) with a fixed radius ($R = 2$ m) and a fixed average speed ($V = 4.3$ m / s) (Figure 11).

In this context, the analysis of these figures in accordance with equation (12), it is possible to say that the power of the wind turbine reacts to the same parameters (R and G) and follows the same physical laws. Figures 9, 10 and 11 are already recorded in Part 5.1 (Figures 6, 7 and 8). This means that by acting on these two parameters (R and V), we can increase or decrease the power of the wind turbine.

The power curve gives many variations:

- Figure 9: we record power variation for a fixed radius and variable speed in a range [1-9 m / s] with a maximum value (P maximum KW = 3) for $a = 0.333$;
- Figure 10: The simulation gives a very significant power versus interference factor.
- Figure 11: The analysis of this figure shows that the power versus interference factor reaches a maximum value of 320 Watt for a value ($a = 0.333$). It maintains the same growth pattern as previous curves.

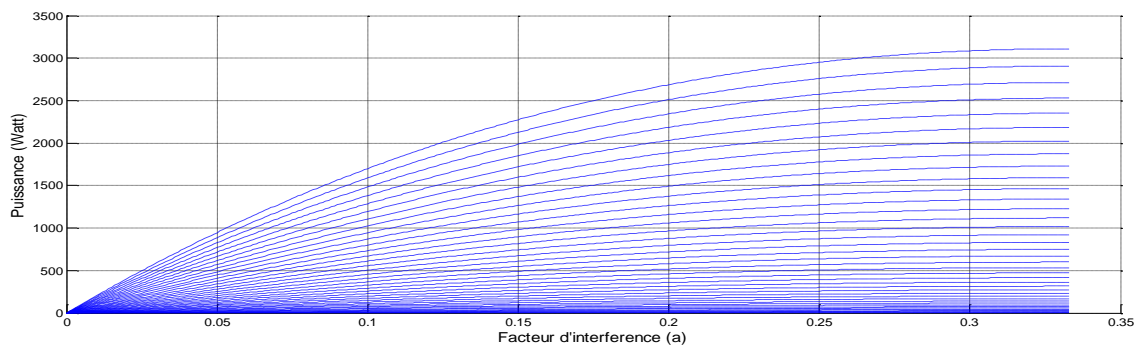


Fig. 9. Power in function with a fixed radius ($R = 2$ m) and velocity distribution $V = [1: 9]$

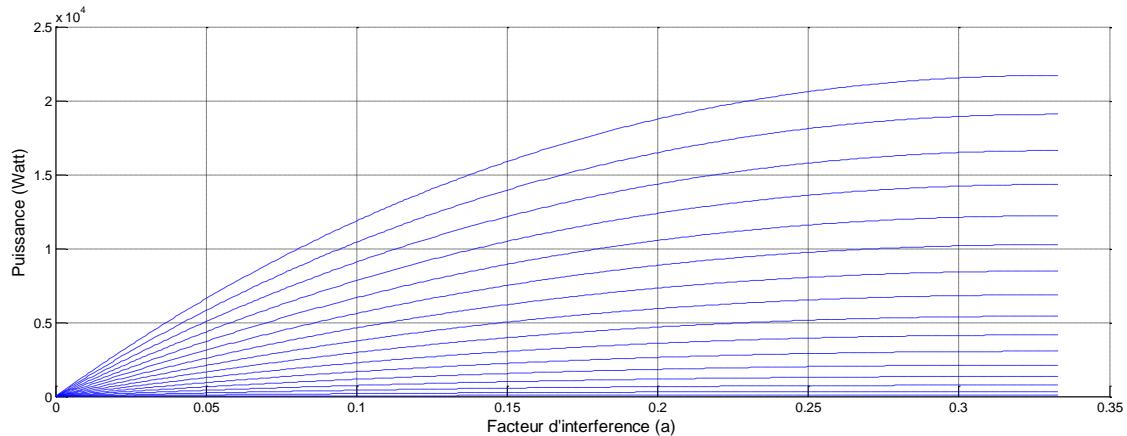


Fig. 10. Power of a wind turbine with a function of a fixed wind speed (average speed = 4.3m / s) and blade radius distribution of the $R = [1: 16]$

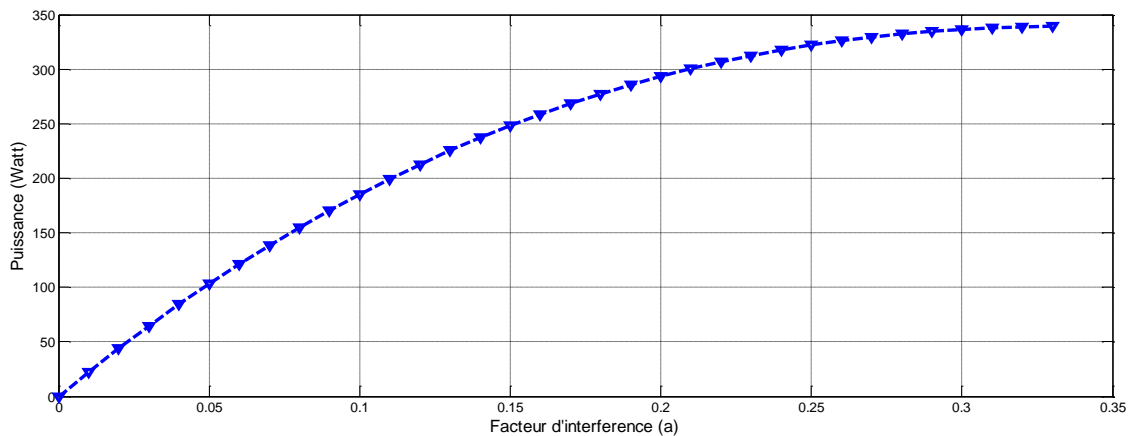


Fig. 11. Power of a wind turbine with a function of a fixed radius ($R = 2\text{m}$) and fixed speed (average speed = 4.3m / s)

From this we found that the simulations follow a similar shape to an increasing exponential function. For figures (9, 10 and 11) respectively, we have shown that the maximum is obtained for an interference factor value of 0.333. The evolution curves Quasi are identical in shape but changes occur in amplitudes. They respond to the same points of interference factor.

Physically this phenomenon can be translated as follows: for a given site and for our type of wind turbine, the maximum value of the power can be found with the interference factor (0.333). The wind speed and radius play a key role in the evolution of the power of the machine.

Thus, we can compensate for the mediocrity of the site across the length of the blades. The more efficient the site, the more we can save on the ground of the turbo engine through the radius of the blades along with the time of their construction.

5.3 Simulation of Profitability Based on the Interference Factor

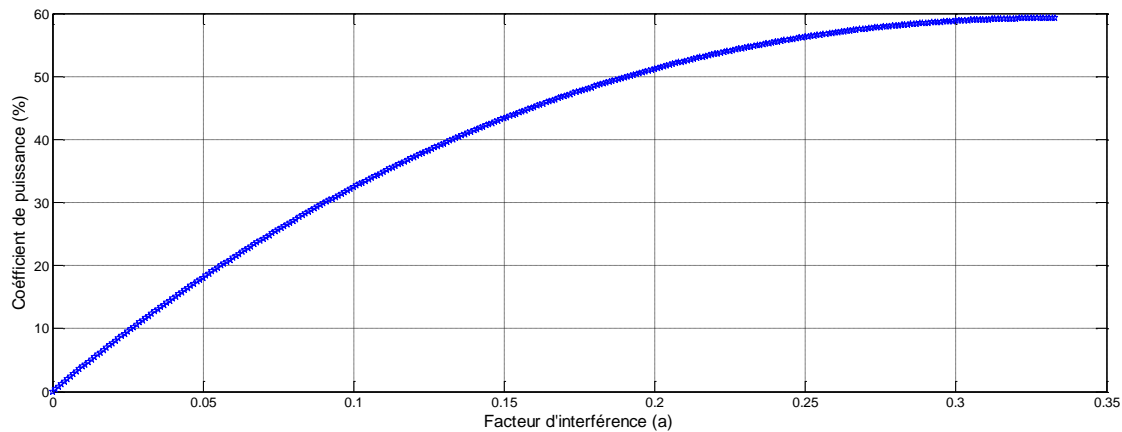


Fig. 12. Aerodynamic efficiency depending interference factor

The yield or performance of the wind turbine depends on its characteristic and the characteristic of the implantation site. For this, equation (17) was simulated. From the analysis of Figure 12 and equation (17), we conclude that the aerodynamic efficiency of the wind generator reaches a maximum value of 0.59 when the interference factor is $a=0.333$.

This result is in agreement with the Betz theory that says aerodynamic performance of a wind turbine may not exceed 59.26% (Betz limit).

6. DISCUSSIONS

The axial force or power, depending on (a) varies V or R , fixing the other parameters, evolves with the same laws that govern similar physical phenomena. We noted that the maximum axial force or power is registered for an interference factor close to ($a = 0.333$). The evolution curves are quasi identical in form, but at different values of evolution, especially those related to the amplitude.

Analyses of these figures are in conformity with the equations (10, 12) and that allow the power of the wind turbine and the axial force to react to the same parameters (R and G) and follow the same physical laws.

This means that by acting on these two parameters (R and V), we can increase or decrease the axial force and then act on the power of the wind turbine.

Thus, we have shown:

- The variation of the radius of the wind turbine blade has a direct influence on the force applied to the rotor and the power of the wind turbine,
- Increasing the speed of the wind acts directly on the axial force and the power of the wind turbine as a function of (a) when the radius is fixed,
- The power of the wind motor and profitability depend on the parameters (V and R) developed in this work.

These results show that the choice of the blades (length, aerodynamic shape), the site (wind speed) are important for the choice of the wind and its implementation option for the production of electricity. These two parameters (R and V) directly influence the axial force and therefore the power of the wind turbine and profitability.

In effect, the power produced by the wind turbine changes proportionally according to the variation of the radius squared of the blades and the wind speed cubed (equation 12). This displays the power and a similarity of action with the axial force. The axial force follows the same physical laws that the evolution of the power produced by the wind turbine; based on the interference factor and parameters (R and G) on production. The axial force varies remarkably with these two parameters as well as the power and efficiency of the turbine.

7. CONCLUSION

We presented a paper on the general theory of the wind engine (turbine) with horizontal axis that was established by Betz [5 and 6] under the following assumptions: axial flow (air movement is not rotating), flow is incompressible and air is passing through the rotor without friction.

Similarly, we have created a representation of the aerodynamic profile of the blade of Matlab wind turbine Bornay3000 (Figure 2). We also developed mathematical models through the physical laws of fluid flow on an aerodynamic shape to find C_p power coefficient and thereafter introduced the modeling portion with both parameters involved, the first time being in the axial force and the second time in power. These include the radius (R) and the wind speed (V). Precisely, the power and the axial force are subject to variations as a function of a , in the simulation.

Numerical simulations are performed using MATLAB software. The proposed models using MATLAB, allowed us to see the evolution of the axial force and the power according to an amount of the variation of the radius along with the variation of the wind.

We then extended our analysis with the study of impacts on the profitability of the wind turbine aerodynamics. It shows that this efficiency is maximized when the value of the interference factor is close to the value of $a = 0.35$.

The results show that the choice of the wind turbine through the length of its blades and sitting through the wind speed are decisive for Wind option, especially for those related to the production of electricity.

This model has allowed the implementation of a simple and useful mathematical method to simulate the fluid interaction (air) and structure (the wind turbine blades). This model shows the behavior of this interaction and give suggestions about the sifting of wind turbines in any site and understand the influence of the interference factor on the profitability and productivity of the wind turbine.

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