Design of Vertical Axis Wind Turbine Darrieus Type (H-Darrieus Rotor) of 0.20 KW from the Software Topsolid

Hagninou E. V. Donnou¹, Drissa Boró², Donald Abode³, Brunel Capo-Chichi³ and Aristide B. Akpo¹

¹Laboratoire de Physique du Rayonnement (LPR), Université d’Abomey-Calavi, 01 BP 526 Cotonou, Bénin.
²Laboratoire d’Energies Thermiques Renouvelables (L.E.T.RE), Université Joseph Ki-ZERBO, Ouagadougou, Burkina Faso.
³Institut National Supérieur de Technologie Industrielle, Université Nationale des Sciences, Technologies, Ingénieries et Mathématiques, Abomey, Bénin.

Authors’ contributions

This work was carried out in collaboration among all authors. Author HEVD designed the study, performed the statistical analysis, wrote the protocol and wrote the first draft of the manuscript. Authors DB and DA managed the analyses of the study. Authors BCC and ABA managed the literature searches. All authors read and approved the final manuscript.

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ABSTRACT

The design of a vertical axis wind turbine (Darrieus type) adapted to the site of Cotonou in the coastal region of Benin was investigated. The statistical study of winds based on the Weibull distribution was carried out on hourly wind data measured at 10 m above the ground by the Agency for the Safety of Air Navigation in Africa and Madagascar (ASECNA) over the period from January 1981 to December 2014. The geometrical and functional parameters of the wind turbine were determined from different models and aerodynamic approaches. The digital design and assembly of the wind turbine components were carried out using the TOPSOLID software. The designed wind turbine has a power of 200W. It is equipped with a synchronous generator with

*Corresponding author: E-mail: donhelv@yahoo.fr;
permanent magnets and has three wooden blades with NACA 0015 profile. The optimal coefficient of lift and drag were estimated respectively at 0.7832 and 0.01578. The blades are characterized by an optimum angle of attack estimated at 6.25° with a maximum fineness of 49.63. Their length is 4 m and the maximum thickness is estimated at 0.03 m with a chord of 0.20 m. The volume and mass are respectively equal to 0.024 m$^3$ and 36 kg. The aerodynamic stall occurs at an attack angle of 14.25°. The aerodynamic force exerted on these blades is estimated to be 240 N. The aerodynamic stresses exerted on the rotor are estimated at 15 864 504 Pa and the solidity at 0.27. The efficiency of the wind turbine is 0.323. From TOPSOLID, the geometrical shape of each component of the wind turbine is represented in three dimensions. The assembly allowed to visualizing the wind turbine after export via its graphical interface. The quantity of annual energy produced by the wind turbine was estimated at 0.85 MWh. This study is the first to be carried out in the study area and could reduce the technological dependence of vertical axis wind turbines and their import for low cost energy production.

Keywords: Design; vertical axis wind turbine; weibull; aerodynamic parameters; topsolid software.

ABBREVIATIONS

- $S$: area swept by the rotor (m$^2$)
- $V$: wind speed (m/s)
- $H$: length of a blade (m)
- $R$: radius of the blade (m)
- $\rho$: density of the air (kg/m$^3$)
- $c$: Weibull scale parameter (m/s)
- $k$: Weibull shape parameter
- $C_p$: wind turbine performance
- $P_m$: mechanical power (W)
- $\omega$: speed of rotation (rad/s)
- $\lambda$: specific speed
- $Pr$: real mechanical power (W)
- $\eta_m$: mechanical efficiency
- $P_{elec}$: electrical power (W)
- $\eta_g$: electrical efficiency
- $P_u$: useful power (W)
- $F_C$: capacity factor
- $V_d$: starting speeds of the wind turbine (m/s)
- $V_n$: nominal speeds of the wind turbine (m/s)
- $V_c$: cut-off speeds of the wind turbine (m/s)
- $V_f$: most frequent speed (m/s)
- $V_{me}$: speed giving the maximum energy (m/s)
- $\eta$: wind turbine performance
- $\sigma$: solidity
- $N$: number of rotor blades
- $C_o$: blade chord (mm)
- $AR_{rotor}$: the rotor aspect ratio
- $AR_{pale}$: the blade aspect ratio
- $W$: relative speed (m/s)
- $U$: rotation of the blade (m/s)
- $V$: wind speed (m/s)
- $\nu$: kinematic air viscosity
- $a$: speed of sound (m/s)
Access to energy is a major challenge for the socio-economic development of the people. Global energy demand is growing exponentially [1] due to population growth, massive industrialization and urbanization. With the progressive depletion of traditional energy resources and their impact on environmental pollution [2-4], the share of renewable energy in the global energy mix has been steadily increasing [5, 6]. Among these sources, wind energy is nowadays, and is likely to continue to be, the main renewable energy source in the electricity mix for years to come [7]. It has grown considerably over the last decade and has become the most sought-after renewable energy source after solar energy [8]. It therefore deserves to be promoted in underdeveloped countries where rural power generation is an acute problem that militates against the socio-economic well-being of the population [9].

In Benin, according to the work of Awanou et al [10], Houekpoheha et al [11], Akpo et al [12], Salami et al [13], Donnou et al [14], the southern coastal region of the country is likely to be home to wind installations for small and large-scale electricity generation. However, this region is exposed to fluctuations in wind speed and direction that could slow down the proper functioning of wind turbines, according to the work of Donnou et al [15]. To cope with these difficulties, vertical axis wind turbines (VAWTs), which are devices with the advantage of being insensitive to changes in wind direction, having a smaller number of components with very low noise emissions and a three-dimensional structural design, are therefore positioned as a credible alternative [7]. Among these types of wind turbines, the Darrieus rotor, which has a natural inability to self-start, is a very promising wind converter in remote and domestic locations with performance at low wind speeds [8]. It is therefore of particular interest to researchers, and in the literature many authors have investigated its design and come up with conclusive results.

This is the case of Tchakoua et al [16] who proposed a new equivalent electrical model for vertical axis wind turbines of the Darrieus type.

\[ \theta \] : azimuth angle (°)  
\[ L \] : lift force (N)  
\[ A \] : blade surface area (m²)  
\[ C_l \] : coefficient of lift  
\[ C_d \] : drag coefficient  
\[ \varepsilon_{\text{max}} \] : maximum thickness of the blade (m)  
\[ V_p \] : volume of the blade (m³)  
\[ M_p \] : mass of the blade (kg)  
\[ \rho_{\text{bois}} \] : density of the wood (kg/m³)  
\[ \sigma_{\text{LE}} \] : elastic limit of the material (Pa)  
\[ E \] : the Young’s modulus of the material (Pa)  
\[ \sigma_{\text{eq}} \] : equivalent stress (Pa)  
\[ \sigma_{\text{ct}} \] : sum of bending and compressive stresses (Pa)  
\[ T \] : sum of torsional and shear stresses (Pa)  
\[ F_{\text{wind}} \] : horizontal wind force (N)  
\[ M \] : bending moment (N.m)  
\[ T \] : shear force (N)  
\[ \sigma_{\text{flexion}} \] : bending stress (Pa)  
\[ \tau_{\text{ cisaillement}} \] : shear stress (Pa)  
\[ F_c \] : compressive force (N)  
\[ F_{\text{centr}} \] : centripetal force (N)  
\[ L_{\text{ax}} \] : length of the rotation axis (m)  
\[ \sigma_{\text{compression}} \] : compressive stress (Pa)  
\[ \tau_{\text{torsion}} \] : torsional stress (Pa)  
\[ I \] : moment of inertia (J/kg.K)  
\[ d \] : diameter of the axis (cm)
The proposed model was constructed from the mechanical description given by the Paraschivoiu multiple double current tube model and is based on the analogy between the mechanical and electrical circuits. Once the operating principle of the DTVAWT has been demonstrated, simulations of the aerodynamic characteristics and those of the corresponding electrical components are carried out and compared. The simulation results obtained agree with the results of the Paraschivoiu double multiple flow tube model found in the literature. An equivalent electrical model for Darrieus-type VAWTs was therefore found to be viable. Parra et al. [17] used numerical simulation to predict the performance of an H-Darrieus vertical axis wind turbine (VAWT). The rotor consists of three straight NACA family aerofoil-shaped blades attached to a rotating vertical shaft. The influence of strength is tested for design trends. Time averaged parameters are used to obtain the characteristic curves of the power coefficient. Batista et al. [7] have proposed a vertical axis wind turbine design with the approach of the multiple dual-flow tube performance prediction model allowing a blade profile capable of self-starting and adequate performance at high top speed ratios. Several field tests are proposed to validate the automatic start, low noise and stable performance of the new rotary wing design. Rogowski et al. [18] estimated the aerodynamic performance of the H-Darrieus turbine, the aerodynamic loads on the blades and the downstream speed profiles behind the rotor. The wind turbine model is based on the rotor designed by McDonnell Aircraft Company. The results obtained indicate that the lift and drag coefficients are consistent with the predictions of the experiment and XFOIL over a wide range of angles of attack. The NACA 1418 airfoil was recommended by the authors in lieu of the original NACA 0018. Alqrurashi and Mohamed [19] analyzed all forces acting on the main parts of the Darrieus rotor during rotation as well as under maintenance and stationary conditions. CFD simulations were used in this work to obtain the different aerodynamic forces on the rotor blades of the Darrieus turbines. The results indicate that the symmetrical S1046 blade has higher forces during rotation and in stationary (static) conditions. In addition, the self-starting capability of the NACA 0021 is better than that of the S1046 due to the low aerodynamic torsion on the S1046 blades. Kumar et al. [8] have worked on the development of VAWT, in particular the Darrieus turbine from the past to the current project. The reason for the technical challenges and past failures is discussed in their study. Various VAWT configurations were evaluated in terms of reliability, components and low wind speed performance. Innovative concepts and the possibility of scaling up to megawatt power generation, especially in offshore environments, were investigated. This work has therefore brought to the forefront the latest information on ongoing developments focusing on decentralized power generation.

These various works aimed at improving the performance of Darrieus-type wind turbines also provide us with a great deal of information on the different techniques used in their design. In the study region and in the West African sub-region very few studies have dealt with the design of vertical axis wind turbines of the Darrieus type. It is therefore essential to have a mastery of the operation and design of this type of aeromotor in order to locally build windmills at a lower cost that can provide electrical energy to populations in rural areas and far from the conventional grid. The objective of this study is therefore to design a vertical axis wind turbine of the Darrieus type adapted to the study site and to evaluate its energy production. Specifically, this work aims to:

- Make a statistical study of the wind in the study area
- Determine the aerodynamic and technological parameters of the wind turbine
- Design of the wind turbine based on these characteristics and assemble it using the Topsolid software.

2. MATERIALS AND METHODS

2.1 Materials

The Cotonou-Airport site, which is our study area, is located in the 125 km long coastal region of Benin. This region extends from Hillacondji in the west to Kraké in the east and is situated between latitude 6°15' N and 7°00' N and longitude 1°40' E and 2°45' E. Hourly wind speed data measured at 10 m from the ground at the Cotonou meteorological station was used for the period from January 1981 to December 2014. Fig. 1 shows the experimental site of the station, the measuring mast and the wind sensor.
2.2 Methods

For the dimensioning of the aeromotor, we started from the generator power to determine the geometric and functional parameters and the various constraints exerted on the axis of rotation.

2.2.1 Power generated by the wind turbine

2.2.1.1. Kinetic power

The kinetic power of the wind generated by the wind is given by equation (1), where S is the area swept by the rotor, which is calculated as $S = 2RH$ for a Darrieus wind turbine [14].

$$P_{vent} = \frac{1}{2} \rho S V^3 = \rho RH V^3$$  (1)

where $V$ is the wind speed (m/s), $H$ is the length of a blade ($H=4m$ in the case of this study), $R$ is the radius of the blade (m), $\rho$ is the density of the air ($kg/m^3$). The wind speed $V$ can be expressed as a function of the Weibull parameters. Equation (1) becomes:

$$P_{vent} = \rho RH c^3 \Gamma \left( 1 + \frac{3}{k} \right)$$  (2)

with $c$ the Weibull scale parameter (m/s) and $k$ the Weibull shape parameter. The values of $k$ and $c$ used in this study are given by the works of Akpo et al [12].

2.2.1.2 Mechanical power

The mechanical power that can be produced by a wind turbine is a fraction of the kinetic power of the wind. This fraction is given by the power coefficient, noted $C_p(\lambda)$, which characterizes the aerodynamic performance of wind turbines. Not all of the energy can be captured by the wind turbine because the speed downstream of the rotor is never zero. Therefore part of the kinetic energy of the wind is not captured. The mechanical power generated by a wind turbine, still referred to as recovered power, is therefore defined as [21]:

$$P_m = C_p(\lambda) \rho RH c^3 \Gamma \left( 1 + \frac{3}{k} \right)$$  (3)

In 1919 a theory was developed by Albert Betz determining the maximum amount of energy that could be extracted from a wind turbine. This maximum corresponds to 59.3% of the power of the wind and is known as the Betz limit. In practice, therefore, $C_p(\lambda)$ necessarily belongs to $[0; 16/27]$. The expression of the aerodynamic torque $C$ that ensures the rotation of the wind turbine blades is expressed as follows:

$$C = \frac{P_m}{\omega}$$  (4)

$\omega$ is the speed of rotation (rad/s). It is expressed as follows [16,18,19]:

$$\omega = \frac{\lambda V_n}{R}$$  (5)

$\lambda$ is the specific speed or reduced speed of the machine, the speed parameter, the feed ratio or forward parameter of the wind turbine, $V_n$ is the nominal wind speed. For each type of wind turbine there is a specific speed that maximizes the coefficient of performance $C_p$. This parameter is therefore frequently used to define the characteristics of wind turbines. It should be noted that the mechanical power varies according to the efficiency of all the mechanical elements, which is generally estimated at 95%. Thus, the real mechanical power noted $P_{r1}$ is written as follows:

$$P_{r1} = \eta_m P_m$$  (6)
where $\eta_m$ represents the mechanical efficiency.

### 2.2.1.3 Electrical power

Permanent magnet alternators were adopted in this study because it is this system that is generally implemented in micro wind turbines. The electrical power generated is expressed by:

$$P_{\text{elec}} = \eta_g P_{\text{el}} = \eta_g \eta_m P_m \quad (7)$$

where $\eta_g$ is the electrical efficiency.

The generator chosen for the design of our device has a power of 200 W with an efficiency of more than 75%. Its characteristics are shown in Table 1. From the power of the generator, the radius of the blades has been determined by the relation:

$$R = \frac{P_{\text{elec}}}{\eta_g \eta_m C_p \rho f c^3 (\frac{2}{15})^3} \quad (8)$$

### 2.2.1.4 Rated and useful power

The rated power of a wind turbine is the maximum electrical power supplied by the generator when the turbine is operating at its optimum operating speed; i.e. when the wind speed reaching it is between its rated speed and/or its cut-off speed. Given the unsteady nature of the wind, a corrective factor has been introduced by physicist Weibull to ensure that the consumer's energy needs are ultimately covered. The relationship between this factor, also known as the capacity factor, and the useful power is [22]:

$$P_u = F_c P_n \quad (9)$$

with $F_c$ the capacity factor given by [22]:

$$F_c = \frac{e^{-\left(\frac{V_d}{\tau}\right)^k} - e^{-\left(\frac{V_n}{\tau}\right)^k}}{e^{-\left(\frac{V_c}{\tau}\right)^k} - e^{-\left(\frac{V_n}{\tau}\right)^k}} \quad (10)$$

where $V_d$, $V_n$ and $V_c$ denote the starting, nominal and cut-off speeds of the wind turbine respectively. The choice of the nominal speed is made by knowing the most frequent speed ($V_i$) on a site and the speed giving the maximum energy $V_{me}$ expressed as follows:

$$V_{me} = \left(1 + \frac{2}{k}\right)^{1/k} c \quad (11)$$

with $V_i < V_n \leq V_{me}$

### 2.2.2 Wind turbine performance

The theoretically possible maximum value of the power coefficient is the Betz limit is $\frac{16}{29} = 0.59$. In addition, it is important to note that the Betz limit does not take into account the energy losses caused when converting the mechanical energy of the wind into electrical energy. Thus, the efficiency of a wind turbine that takes into account all the successive degradation of the wind energy is expressed as [23]:

$$\eta = \frac{P_u}{P_{\text{vent}}} = C_p \eta_m \eta_g \quad (12)$$

The values of $C_p$ as a function of $\lambda$ are given in Fig. 2.
2.2.3 Characteristic parameters (geometrical, aerodynamic and functional) of the wind turbine

2.2.3.1 Determining the number of blades

Determining the number of blades in a wind turbine depends on many factors, such as the lightness of the turbine's mechanism, which promotes the efficiency of the turbine and size. In terms of dynamics, the three-blade configuration is the most balanced. In terms of loads, the force exerted on the structure (the tower) is proportional to the number of blades. In fact, the wind exerts a force parallel to its direction on each of the blades. This force is proportional to the surface encountered by the wind. The greater the number of blades, the greater the surface area in specific limits. A large number of blades requires the use of a more robust and expensive structure with a low efficiency. A two or one-blade wind turbine is not recommendable because of the heavy impacts on the blades every time they passed in front of the supporting tower. These different elements justify the choice of the three-blade configuration, which is a compromise.

2.2.3.2 Choice of blade profile

The choice of the aerodynamic profile is most often made using numerical fluid dynamics methods and less often using experimental tests [25, 26]. Many authors have studied the aerodynamic performance of VAWTs equipped with a specific type of airfoil, usually the NACA 00XX [18]. This is the case of Mohamed et al [27] using many types of symmetrical and asymmetrical airfoils, who have shown that the symmetrical NACA 0015 airfoil has a high aerodynamic efficiency that is as high as the best among the tested airfoils. According to a study carried out at the University of Windsor in Canada analyzing the performance of several airfoils for a Darrieus rotor, the NACA0015 also showed better performance [28]. Some asymmetrical airfoils such as the NASA LS-0417 or NACA4415 produce more torque on start-up but the NACA0015 performs better overall. In addition, many authors choose this same profile when studying VAWTs and consider it as the ideal profile for this type of wind turbine. Based on these different works, this profile was therefore used in the present study. The NACA 0015 profile has a relative camber of 0% with a maximum value of 0% of the chord and has a relative thickness of 15% of the chord. The length of the chord, also called blade width, has no influence on the power of the wind turbine, but it does influence the starting torque: the wider the blade, the higher the starting torque will be. In our case, it is therefore important not to oversize the width of the blades, otherwise the wind turbine will stop more often during operation. The blades should not be undersized either, as this could lead to a loss of efficiency. For a good compromise, we have therefore chosen to use the $C_0$ string equal to 0.20 m.

2.2.3.3 Solidity

The rotor strength $\sigma$ is the main parameter to define the geometry of the vertical axis wind turbine. It expresses the proportion of the area swept by the rotor that is occupied by the blades. There are several definitions, but the one used in this study is given by [19]:

$$\sigma = \frac{N C_0}{2 R}$$

(13)

where $N$ corresponds to the number of rotor blades ($N = 3$ in this study), $C_0$ is the chord and $R$ is the radius of the blades. In general, Darrieus wind turbines are in a fairly wide range of strength between the following values: $0.05 \leq \sigma \leq 0.5$.

2.2.3.4 Aspect ratio

A wind turbine can be characterized by two different aspect ratios (elongation), denoted AR: the rotor aspect ratio and the blade aspect ratio. The first is the ratio between the length $H$ of a blade and the diameter radius of the rotor, the second is the ratio between the length of a blade and the mean chord. The relationships are defined as [28, 29]:

$$AR_{\text{rotor}} = \frac{H}{2R}$$

(14)

$$AR_{\text{blade}} = \frac{H}{C_0}$$

(15)

2.2.3.5 Relative speed

The benefit with the Darrieus wind turbine is that, depending on the position of the blade, it does not see the wind coming from the same direction. When it rotates, and the wind comes from a given direction, it creates its own wind which is the tangential wind $U$ associated with the $V$ wind, and we thus obtain a $W$ wind called apparent wind; and depending on the position of the
profile, this $W$ wind will not come from the same direction. This wind is the resultant coming from the addition of the two vectors: the incident wind in the direction of the local flow tube $V$, and the wind due to the rotation of the blade ($U = R \omega$) which is tangential to the trajectory. In fact, it is said that the rotor turns the wind or roll up the wind that is incident on it. It is the speed of this wind which is referred to as the relative speed $W$. It can be obtained from [19, 30]:

$$W = \sqrt{V^2 + U^2}$$

(16)

### 2.2.3.6 Reynolds number

The Reynolds number is very important for the modelling of VAWTs. It is used to characterize the flow regime perceived by the blades. It is also used to identify the curves that will be used to determine the lift and drag coefficients as well as the angles of attack and stall. It is expressed as follows [18, 31]:

$$Re = \frac{R \omega C_o}{v}$$

(17)

with $C_o$ the blade chord, $v$ : kinematic air viscosity

### 2.2.3.7 Number of match

The Mach number provides information on whether the flow is compressible or not. As with the Reynolds number, a velocity characteristic value is used to have a single dimensionless parameter for an operating condition, which is compared to the sound speed and noted $a$. Its expression is given by equation (18). Its value is usually very low in the context of small wind turbines, in the range of $10^{-4}$ to $10^{-1}$ [32].

$$M = \frac{R \omega}{a}$$

(18)

The speed of sound is 340 m/s.

### 2.2.3.8 Angle of attack

The angle of attack or angle of incidence $\alpha$ is the angle formed between the profile chord and the relative velocity vector $W$ in the profile plane. A relationship that relates the angle of attack to the azimuth angle $\theta$ and the specific velocity ratio $\lambda$ is [16, 19, 30]:

$$\alpha = \arctan \left( \frac{\sin \theta}{\lambda \cos \theta} \right)$$

(19)

The variation of the angle of attack $\alpha$ during a Darrieus blade turn at different values of speed $\lambda$ is shown in Fig. 3. It can be seen that the range of the attack angle becomes small as the top speed ratio rises. There is an angle of attack that is roughly common to all profiles (between 10° and 15°), and at this angle the lift drops abruptly and the drag increases sharply: this is the aerodynamic stall. During a complete revolution of the Darrieus wind turbine for a specific speed $\lambda = 4$, the angle of attack only varies between -15° and 15° unlike the other values in $\lambda$. Therefore, in order to prevent the stall phenomenon from intensifying over time or not enough torque at start up (for some values from $\lambda$), we have therefore opted for the estimated value of 4 for the top speed in the case of this study.

![Fig. 3. Variation of the azimuth angle $\theta$ with the angle of attack $\alpha$ for one revolution at different top speed ratios $\lambda$ [19]](image-url)
2.2.3.9 Stall angle

The coefficient of lift increases with incidence but this growth has a limit. From a certain angle of attack, the coefficient of lift drops abruptly and this leads to a drop in the aerodynamic performance of the profile. This phenomenon is known as a stall. The angle at which the stall occurs is called the static stall angle, and depends on the profile, the fluid and the Reynolds number. Since the angle of attack as seen by the blade is higher the lower the specific λ speed is the stall becomes more and more important for low λ values.

2.2.3.10 Forces applied to the blade

At low angles of attack, the air-flow along the blade is laminar and is faster on the extrados than on the intrados. The resulting vacuum on the upper surface creates a force that draws the blade upwards (forward). This force is called lift $L$:

$$L = 0.5 \rho AW^2 C_l$$

(20)

where $C_l$ is the coefficient of lift, $A$ is the blade surface area (m²), $\rho$ is the air density (kg/m³), $W$ is the relative velocity (m/s).

As the surface area exposed to the direction of air flow increases, an air resistance force appears. This resistance force, called drag and noted $D$, is expressed by:

$$D = 0.5 \rho AW^2 C_d$$

(21)

where $C_d$ is the drag coefficient. Lift and drag apply to the aerodynamic centre of the profile, located at approximately 25% chord. The coefficients of lift $C_l$ and drag $C_d$ are highly dependent on the angle of attack $\alpha$ and the profile. The total force $F$ applied to the blade is the sum of lift and drag.

2.2.3.11 Finesse

The fineness of a profile is the ratio of the coefficient of lift $C_l$ to that of the drag $C_d$. It represents, among other things, the efficiency of a blade [33].

$$\text{Finesse} = \frac{C_l}{C_d}$$

(22)

As variable that varies according to the angle of attack, there is then a maximum angle of attack. This angle is called the optimum angle of attack and is noted $\alpha_{opt}$. To obtain its value, we use what is called profile polar. It is a curve that shows the evolution of the lift to drag ratio as a function of the angle of attack for a given Reynolds number. To obtain this curve, either wind tunnels or virtual wind tunnels on the Internet are used. In the case of this study, the value was obtained directly from the online tools on the airfoil tools site. The maximum fineness and the corresponding optimum angle of attack were determined.

2.2.3.12 Thickness, volume and mass of the blades

The material chosen for the manufacture of the blades is wood. The maximum thickness, volume and mass of the blade are given respectively by [28, 29]:

$$e = 0.15 C_0$$

(23)

$$V = e C H$$

(24)

$$M = V \rho_{\text{bois}}$$

(25)

$\rho_{\text{bois}}$ is the density of the wood (1500 kg/m³).

2.2.4 Dimensioning the axis of rotation

The function of the vertical axis is to transmit the torque produced by the blades to the generator. It is therefore essential that this shaft be rotationally linked to the blades and the generator. In order to avoid more complex and costly machining processes, such as turning, a constant diameter shaft will be used to make the shoulders and rotational connections. The solution we have opted for is the use of a flanged water/gas pipe. The steel bars that will be used for the blade-axle rotation connection will be drilled at two points at each end to be bolted to the flanges of the axis.

2.2.4.1 Static dimensioning

The aim of this approach is to ensure that the effect of stress on the material will not lead to plastic deformation. It is therefore essential that the maximum stress remains below the yield strength of the material. This can be written as [28, 29]:

$$\sigma_{eq} \leq \frac{\sigma_{LE}}{k_{Ec}}$$

(26)
with \( \sigma_{EL} \) the elastic limit of the material \((\sigma_{EL} = (3.55E + 11 \text{Pa}), E \) is the Young's modulus of the material \((E = 2030000 \text{ Pa})\), ksec a safety coefficient equal to 2. It is recommended when designing objects that operate in an ordinary environment and whose stresses and strains can be determined. The equivalent stress \( \sigma_{eq} \) obtained according to the Von Mises criterion is given by [28, 29]:

\[
\sigma_{eq} = \sqrt{\sigma_{ct}^2 + \tau^2}
\]  

(27)

with \( \sigma_{ct} \) the sum of bending and compressive stresses and \( \tau \) the sum of torsional and shear stresses.

2.2.4.2 Constraints

The most critical case can be reduced to a two-dimensional static problem of a shaft on two supports as shown in Fig. 4. Gravity is neglected and the forces are considered punctual.

**Bending and shearing**

The bending and shear stresses are due to the horizontal wind force, which is expressed according to equation (28) [29]:

\[
F_{wind} = \frac{1}{2} \rho AV_c^3
\]  

(28)

with \( V_c \): the wind cut-off speed, \( A \) is the blade surface area \((\text{m}^2)\), \( \rho \) the air density \((1.225 \text{ kg/m}^3)\). It results from the sum of three times the area of a blade face and the projected area of the connecting bars on the normal wind plane.

The bending and shear stresses are then given by equations (29) and (30) with \( d \) being the diameter of the axis of rotation, \( M \) the bending moment and \( T \) the shear force [28, 29]:

\[
\sigma_{flexion} = \frac{32M}{\pi d^2}
\]  

(29)

\[
\tau_{cisaillement} = \frac{4T}{\pi d^2}
\]  

(30)

The bending moment is given by the following expression [28]:

\[
M = \frac{F_{wind} L_{ax}}{16}
\]  

(31)

The shear force \( T \) is expressed as follows:

\[
T = 0.5F_{wind}
\]  

(32)

\( L_{ax} \) is the length of the rotation axis. In this study the diameter and length of the axis were set at 4 cm and 2 m respectively.

**Compression**

In rotation, the blades will undergo a centripetal force given by equation (33) [28, 29]:

\[
F_{centr} = M_p \omega^2 R
\]  

(33)

![Fig. 4. Diagram of the different forces acting on the axis [28, 29]]
with $M_p$ the mass of a blade. The compressive force acting on the shaft at the connections is [29]:

$$F_C = 3e_{\text{max}}F_{\text{centr}}$$

(34)

The compressive stress is calculated as follows [29]:

$$\sigma_{\text{compression}} = \frac{4F_c}{\pi d^2}$$

(35)

+ **Torsion**

Equation (36) then gives the torsional stress [28, 29]:

$$\tau_{\text{torsion}} = \frac{16C_0}{\pi d^3}$$

(36)

2.2.5 Buckling sizing

The centre line under normal compression will tend to bend and deform in direction perpendicular to the compression load. This phenomenon is called buckling. In contrast to static and fatigue sizing, it is considered here that the stresses are applied to the deformed axis.

The theoretical critical buckling load is then given by the Euler formula [28]:

$$F_C = \frac{E I}{L_x^2}$$

(37)

with $F_C$ the compressive force, $E$ the Young’s modulus of the material, $I$ the moment of inertia of the section (J/kg.K), $L_x$ the buckling length of the pin. The moment of inertia of the shaft cross section is given by [29]:

$$I = \frac{nd^4}{64}$$

(38)

The bending of the axis is expressed as follows:

$$f = \frac{F_{\text{wind}}L_x^2}{3EI}$$

(39)

3. RESULTS ET DISCUSSION

3.1 Wind Statistics

Figs. 5 and 6 show the frequency distribution and the theoretical energy curve.

![Fig. 5. Frequency distribution of wind at the site](image)

![Fig. 6. Theoretical energy curve](image)
The analysis of Fig. 5 indicates that the most frequent wind speed at the study site is estimated to be 4 m/s. A large proportion of the winds above 10% are between 2 m/s and 6 m/s and wind speeds above 10 m/s have a frequency of occurrence of less than 1%. The theoretical energy production curve of the wind turbine (Fig. 6) shows a peak of 366,303 kWh/year at 6 m/s.

Based on this wind and energy distribution, the wind speed giving the maximum energy is estimated to be 6 m/s and wind speeds of at least 2 m/s have a high frequency of occurrence at the study site. Based on these characteristics, the starting speed of the wind turbine was set at \( V_s = 2 \) m/s and the nominal speed \( V_n = 6 \) m/s. Winds above 12 m/s rarely occur at the study site. The cutoff speed \( V_c \) of the wind turbine was therefore estimated to be 12 m/s. The energy output of the 200W wind turbine was estimated at 2324 Wh/day.

Fig. 7 shows the wind rose of the study site. The most dominant directions at the site are SSW and SW. The SSW directions have a frequency of occurrence of 75% against 12.5% for the SW direction. The majority of the winds therefore come from the Atlantic Ocean and the other directions are not very noticeable. The study site is thus dominated by sea breezes as well as the West African monsoon which is a thermal wind that originates in the open sea thanks to the Saint Helena High.

3.2 Characteristics of the Wind Turbine

3.2.1 NACA Profile 0015

Fig. 8 gives an overview of the NACA 0015 profile. It was drawn using the Airfoils online tool by integrating the values of the chord, the Reynolds number obtained and the \( N \) parameter which describes the roughness of the aerodynamic profile of the blade. In the case of this study for an average wind tunnel, \( N_{\text{crit}} \) is equal to 9.

3.2.2 Profile polar variation

Fig. 9 shows the variation of the lift to drag ratio as a function of the angle of attack. The analysis of the graph indicates that the maximum blade profile fineness is estimated to be 49.63 and the angle of attack corresponding to this value is the estimated optimum angle of attack of 6.25°.
In Fig. 10, the variation of the coefficient of lift and drag as a function of the angle of attack is shown. Note that from the value $\alpha = 14.25^\circ$, the coefficient of lift ($C_L$) begins by decreasing from 1.2139 to 0.9052 for an angle of attack of 16.75$^\circ$ thus resulting in an increase in the coefficient of drag from 0.04600 to 0.12012. The aerodynamic stall is therefore obtained from $\alpha = 14.25^\circ$.

The aerodynamic parameters obtained for the NACA 0015 profile (lift, drag, angle of attack, stall angle, etc.) were compared with the values observed in some works taken from the literature such as those of Rogowski et al. [18], Boumrar [34] and dealing with the same profile. The results show that the stall obtained by Rogowski et al. [18] is light and does not suffer from a
sudden drop in aerodynamic profiles, contrary to the lift profile observed in this study, where the stall is somewhat abrupt. This could be due to the weather conditions observed at the study site. The coefficient of lift and drag are of the same order of magnitude.

### 3.2.3 Numerical values

Table 1 summarizes the values obtained for the characteristics of the H-Darrieus VAWT.

The different values obtained for the characteristics of the H-Darrieus VAWT wind turbine were then used for the design of the device using the TOPSOLID software. Comparing some of these parameters obtained with the work of Bekhta and Zeblane [35], we notice that the number of blades, the chord and the type of profile obtained by these authors are close or similar to the values obtained in this study.

### 3.3 Components of the H-Darrieus Rotor Modelled by Topsolid

Computer-aided design (CAD) is today an essential tool in the field of manufacturing or designing technical objects. It enables design calculations to be materialized, the performance of new or existing systems to be evaluated using the simulation tools available, and modifications to be made without having to spend any money.

In the case of this study we used the design software Topsolid. The first step was to design the various VAWT elements, namely the blades, the tie rods, the axis of rotation, the generator and the mast. The material used for the design of the blades is glass-fiber reinforced wood and plastic. The 40 mm diameter shaft is made of stainless steel as well as the connecting bars. Figs. 11, 12, 13, 14 show the modelled components.

Then we proceeded to assemble the different components to obtain the structure of the wind turbine in Fig. 15.

In short, the careful study of the main components of H-Darrieus VAWT is crucial in the design of the latter because its performance results from the combination of the efficiency of each of these components. Computer Aided Design (CAD) is also a necessity in the design process, as it allows us to have a picture of the realism, avoid making mistakes that could lead to unnecessary expense and achieve the desired performance.
<table>
<thead>
<tr>
<th>Designation</th>
<th>Value</th>
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<tr>
<td>Wind turbine operating characteristics</td>
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<tr>
<td>Starting wind speed $V_d$ (m/s)</td>
<td>2</td>
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<tr>
<td>Nominal wind speed $V_n$ (m/s)</td>
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<tr>
<td>Wind speed at cut-off $V_c$ (m/s)</td>
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<td>Specific wind ($\lambda$)</td>
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<td>Performance coefficient ($C_p$)</td>
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<td>Mechanical efficiency ($\eta_m$)</td>
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<td>Generator</td>
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<tr>
<td>Type</td>
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<tr>
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<tr>
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<td>Voltage (VDC)</td>
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<td>Generator diameter (mm)</td>
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<td>Rotational speed (rpm)</td>
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<td>Torsional stress ($P_a$)</td>
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<td>Shearing effort (N.m)</td>
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<td>Buckling ($P_a$)</td>
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<tr>
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<td>Value</td>
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<tr>
<td>Flexion ($P_2$)</td>
<td>0.044</td>
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<tr>
<td>Height (m)</td>
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<td>Performance ($\eta$)</td>
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<tr>
<td>Air density $\rho$ (kg/m$^3$)</td>
<td>1.225</td>
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</tbody>
</table>

**Fig. 13. Alternator without its axis**

**Fig. 14. Axis-blade connection**

**Fig. 15. Structure of the H-Darrieus rotor**
4. CONCLUSION

This study focused on the design of a vertical axis wind turbine of the Darrieus type using Topsolid software. Based on the wind statistics recorded by the meteorological station of Cotonou-Airport for the period from January 1981 to December 2014 at an altitude of 10 m, the aerodynamic, functional and electrical parameters of the wind turbine were determined. The computer-aided design under the Topsolid software using the determined parameters was finally carried out. The main results obtained can be summarized as follows:

- the wind turbine has a power of 200 W and is equipped with a permanent magnet synchronous generator. It has three wooden blades with a NACA 0015 profile. 
- the blades are characterised by a length of 4 m, a maximum thickness of 0.03 m, a chord length of 0.20 m, an optimal angle of attack evaluated at 6.25°, a fineness of 49.63, a volume of 0.024 m³, a mass of 36 kg, an aerodynamic stall observed from 14.25°. The optimal lift coefficient of the blades is 0.7832 and the drag coefficient is estimated at 0.01578. The specific speed of the blades is estimated at 4.
- the aerodynamic force exerted on these blades is estimated at 240 N. The aerodynamic stresses exerted on the rotor are estimated at 15864504 Pa and the strength at 0.27. The inertia of the axis of rotation and the bending moment have been estimated at 7.85x10⁻⁵ J/kg.K and 133 N.m respectively.
- the efficiency of the wind turbine is 0.323 with a starting speed of 2 m/s, a nominal speed of 6m/s and an estimated cut-off speed of 12 m/s.
- the average daily energy production of the wind turbine is estimated at 2324 Wh.

In sum, this work made it possible to determine the characteristics of the components of a Darrieus (0.2 kW) wind turbine adapted to the Cotonou site. Other higher power ranges could also be studied and carried out in the study region at a lower cost and thus reduces the importation of this machine type. Determining the aerodynamic properties of this wind turbine in the wind tunnel and confirming these numerical results by an experimental device in the future could also improve the designed model.

DISCLAIMER

The products used for this research commonly and predominantly use products in our area of research and country. There is absolutely no conflict of interest between the authors and producers of the products because we do not intend to use these products as an avenue for any litigation but for the advancement of knowledge. Also, the research was not funded by the producing company rather it was funded by personal efforts of the authors.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

REFERENCES


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