Experimental Contributions for the Study of the Technical Characteristics of a Prototype of Multibladed Wind Turbines for Mechanical Energy Generation for Water Pumping

Eduardo San Martin[1], Rogério Apolinário[1], Mário Rosado[1], Daniel Barreira[1], José Manuel[1], Akihito Esperança[1*], Vencislau Quissanga[1*]

[1]Higher Polytechnic Institute of Technology and Sciences (ISPTEC), Av. Luanda Sul, Rua Lateral, Via S10, Talatona, Luanda, Angola
(Corresponding Author E-Mail: akihito.esperanca@isptec.co.ao* and vencislau.quisssanga@isptec.co.ao*)

Abstract: ***Given the importance of water and electricity in the different sectors of development of a nation and in the daily life of human beings, it is essential to develop investigations and/or studies related to the alternatives of micro-electric power stations to facilitate the process of supplying the precious liquid, especially in regions with notable shortages or even drought. In this context, in addition to water distribution for sustainability, it is important that supply systems are built in order to significantly reduce water losses and energy consumed by pumping equipment in the operating phase. Thus, the present research work aims to contribute with some experimental responses based on the technical characteristics of a prototype wind turbine of the multi-blade type. Therefore, as a case study, a horizontal axis wind turbine with a multi-blade rotor was developed / built, taking into account the high starting torque. In the study in question, three variations of the number of blades (three, nine, and eighteen) were adopted, with blades with a thickness of 1 mm, a diameter of 0.42 m, and a rotor of 1 m, to evaluate the power and efficiency of the turbine. Taking into account the variation in wind speed and the variation in the angle of attack. Therefore, the results were compared, and it was concluded that the most viable configuration is the case with 18 blades with an angle of attack of 45 degree. Therefore, these results were taken as a basis for the real design project of a pilot plant for pumping water in a farm located in the province of Bengo-Angola.***

Keywords: Multi-bladed wind turbines; Horizontal Axis; Experimental prototype; Pilot plant; Water pumping

1. Introduction

In the current global scenario where concern for the environment and the future of the planet is at its peak, wind energy is gaining more and more space in terms of energy alternatives to reduce dependence on conventional energy sources of fossil origin, which in addition to having limited resources, are extremely harmful to the environment. The growth of wind energy production is due to the fact that it is a totally renewable, clean, and environmentally advantageous source because it does not produce any type of pollutant [1–4]. Furthermore, wind energy is the energy produced by means of the wind that has been used for centuries as a source of energy by mankind. That is, wind energy results from the transformation of wind energy into mechanical energy through windmills, or kinetic energy. This form of energy can be converted into more useful forms of energy through wind turbines to produce electrical energy. Other applications refer to the direct transmission of mechanical energy from the turbine for pumping water or aerating aquaculture tanks [5–7]. In this context, Angola stands out as one of the countries with a good wind potential with around 3.9 GW, as illustrated in Figure 1; many regions with extremely attractive average wind speeds for wind power generation. Highlighting that this fact widely encourages engineers and researchers to develop projects in related areas, to provide answers to possible existing problems.

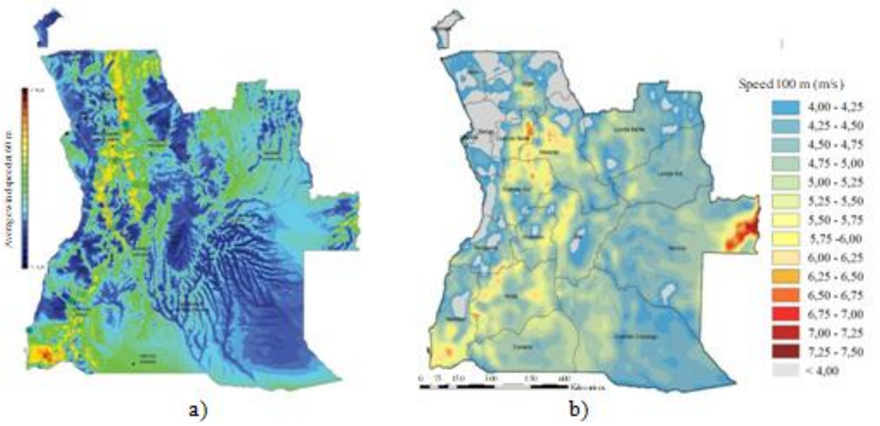

Figure 1: Mapping of wind resources in Angola; a) wind potential; b) average wind speed [Adapted from [8, 9]).

Wind energy can represent a technical, economic, and environmental solution for the population in rural areas of Angola. This technology, despite being well known and used in many countries, is practically unknown in many countries on the African continent, especially in Angola.

In rural areas, pumping water is an activity of great importance and needs for livestock, land drainage, irrigation, and domestic supply. To cover these activities, diesel or gasoline motor pumps are used with the corresponding associated costs and the environmental contamination caused by the engines.

2. Methodology and Experimental Program

2.1 Methodology and application

The present research work was carried out with the objective of determining the technical characteristics of a model of the multipass turbine (multibladed), for coupling piston pumps, (water pumping) destined for rural areas located in the commune of funda Kilunda, municipality of Dande in the province of Bengo-Angola. In order to fulfill the objectives, descriptive research was carried out and as a research technique, an 18-blade turbine was adopted as a case study, made of steel blades 1 mm thick and 0.42 m long and with a 1m rotor diameter that supports studies centered on wind load using local data. The evaluation carried out consists of determining which angle with this type of blades, in which power and efficiency are maximized for different wind speeds, will be more viable when applied in the local context (in the Kilunda sling).

The intended evaluation consists of the need to find and/or reveal which angle with this type of blades, in which power and efficiency are maximized for different wind speeds, will be more viable when applied in the local context, namely in the Kilunda sling.

The characteristic parameters of the wind were obtained in accordance with the prescriptions of the standards [10], with local measurements and compared with data on the speeds that occurred, organized by the National Institute of Meteorology and Geophysics (INAMET), the body responsible for controlling the incident speed at the level of all the provinces of Angola, through a sophisticated radar, with the intention and the need to guard against possible oscillations, taking into account the possible negligence [11, 12].

As already mentioned, in this research work the dynamic impact of the wind was evaluated, based on the use of a wind tunnel, an instrument that is found and used in the laboratory of the institution of affiliation of the authors in question (ISPTEC). Finally, based on the software in question, the minimum wind speed is determined for the turbine to start with certain loads defined for pumping water, whose results served as a basis for presenting the technical characteristics of a prototype multiblade turbine, for designing a pilot plant for pumping water at the deep Kilunda farm.

3. Types of wind turbines

3.1 Vertical axis wind turbines

Vertical axis system turbine mills use Savonius or Darrieus blades, as shown in Figure 2. The advantage is that they are generally cheaper than those with a horizontal axis and that they do not need an orientation mechanism in relation to the direction of the incident wind. In addition, the other advantage is the ease of installation and maintenance, since most of these turbines have their equipment mounted on the ground. Therefore, as already mentioned, these systems can produce torque with the wind coming from any direction with a wind speed reduced by about 8 km/h [13].

According to [13–15], these types of turbines have blades that are arranged on the vertical axis and are rotated by the wind and, therefore, do not require a yaw mechanism ("yaw"), as they can take advantage of the wind from any direction. Generally, these operate closer to the ground, allowing the placement or replacement of heavy equipment more easily. However, this aspect consists of a notable disadvantage, since the winds are much lower when it comes to wind close to the ground, therefore exerting less power.

a) b)

Figure 2: Vertical axis wind turbine a) Darrieus rotor and b) Savonius rotor [16–18].

3.2 Horizontal axis wind turbines

In the horizontal axis wind turbine Figure 3, the rotor axis orientation is maintained along the horizontal axis, which can be adjusted so that it is parallel to the wind current direction. The rotation speed of multi-blade wind turbines is 60 to 80 rpm [14, 17], and this type of turbine usually contains a tower to lift the turbine components to an ideal height for a wind speed of 80 to 100 m [19, 20]. The blades are situated downwind and therefore capture the wind and rotate in the direction of the wind. The rotor is the part responsible for extracting the kinetic energy from the wind and converting it into rotational energy. The rotor is responsible for transmitting the rotation movement to the main shaft and this converts it into mechanical energy [17, 20–22]. It should be noted that these systems, despite having a higher cost than vertical axis systems, have greater efficiency and yield. Therefore, they are the best-known and most used in power generation [23].

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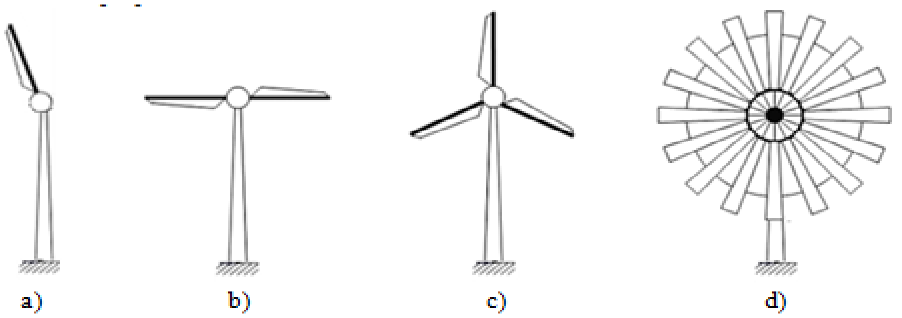

Figure 3: Wind turbine with horizontal axis rotor; a) single blade turbine, b) two-blade turbine, c) three-blade turbine, and d) multiblade turbine (Adapted from [23]).

In this way, it can be stated that multi-blade wind turbines have been widely used in water pumping due to the high torque they provide at low wind speeds. These turbines fit very well with piston pumps, as they have low rotational speed and high torque.

Wind water pumping systems consist of a rotor that converts wind energy into rotating motion. The diameter of the rotor is about 2 to 6 m with 15 to 40 steel or galvanized blades, a gearbox mechanism driven by the blades that convert the fan's rotational motion into reciprocating motion, and a puller that descends from the windmill. into the well to transfer energy to the underground pump which, with each movement of the suction rod, draws the water up through a one-way check valve (see Figure 4) [24, 25].

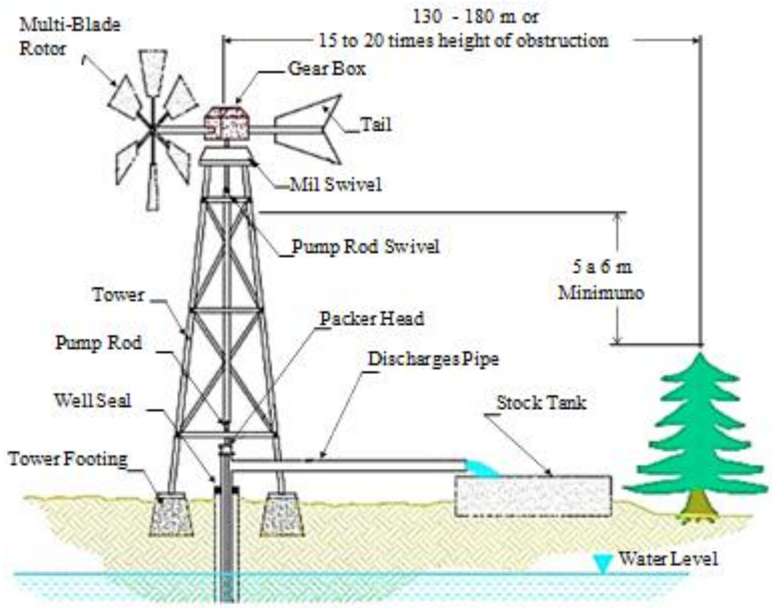

Figure 4: Components of the wind turbine system (Adapted from [26]).

According to [17, 27], the wind blows with a minimum speed of about 2.5 – 3 m/s, it rotates the blades around an axis, and the axis drives a gear mechanism that converts the rotary motion into an up-and-down movement, the movement triggers a long puller rod and generates the necessary force to lift the piston and the water it contains, thus the pumping process begins.

3.2.1. Power coefficient

The power coefficient is the ratio between the power extracted by the turbine and the power available in the wind (wind energy). Then it is mathematically expressed in Eq.1, the coefficient of power (cp). Where, Pt is the power extracted by the turbine and Pw is the power available from the wind [28].

$$C_p = \frac{P_t}{P_w} \quad (1)$$

The power extracted by the turbine is determined mathematically based on Eq.2. It is worth mentioning that the Betz limit is the maximum possible value for Cp which is equal to 16/27, but the ideal possible value for a multi-bladed wind turbine is 30% [19].

$$P_p = \frac{1}{2} \cdot \rho \cdot A \cdot v^3 \cdot C_p \quad (2)$$

3.2.2. Swept area

Swept area is the section of air that surrounds the wind turbine or windmill in its motion and interacts with the rotors to produce the rotational motion [29]. The scanned area (As) for the HAWT is calculated based on Eq.3.

$$A_s = \frac{\pi \cdot D^2}{4} \quad (3)$$

3.2.3. Tip speed rate

Tip speed rate is the ratio of the characteristic speed of the windmill rotor tip, which depends on the turning radius R in □ (radians per second) to the wind speed v (m/s) [29]. It is

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represented mathematically according to Eq.4.

$$\lambda = \frac{\omega \cdot R}{v} \quad (4)$$

3.2.4. Solidity

Solidity is the ratio between the area of the blades and the swept frontal area of the wind turbine, in a perimeter corresponding to 70% of the radius of the blades. In the case of horizontal axis wind turbines, n is the number of blades, C is the average length of the chord and R is the radius of the rotor blade (see Eq.5). In this way, it can be said, therefore, that the greater the area of the propellers, obviously, the greater the sweeping area and with that, the greater the solidity of a given turbine. The solidity of the turbines is symbolically represented by the Greek letter sigma [30].

$$\sigma_i = \frac{n \cdot C}{R} \quad (5)$$

3.2.5. Water pump output power

The power required to pump water (W) is normally determined by the flow rate and the total head generated. As shown below in Eq.6. Where: ρ density of water (kg/m3), g acceleration due to gravity (m/s2), Q flow rate (m3/s), H total pumping head in a meter of water (m) [19]. Then shown in Figure 5 is the wind system flowchart.

$$P_w = \rho_w \cdot g \cdot Q \cdot H \quad (6)$$

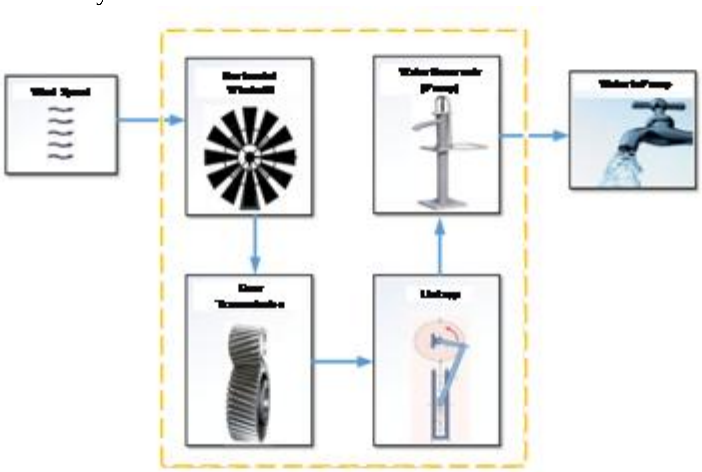

Figure 5: Wind system flowchart (Adapted from [31])

3.3. Assembly of the project's experimental installation

The horizontal windmill rotates by wind energy transmitted by the spur gear through the rotating shaft. The spur gear shaft is engaged by the pump which pumps water from the water source. In the case of turbine installations, it is important to note that the mast is mounted against the turbine wind in the direction from which the most valid wind was expected to come during the test. In this context, meteorological data are generally recorded with a sampling rate of 1 second and are stored in periods of 1 minute in which the average wind speed, minimum, maximum, and standard deviation are recorded [32].

4. Case study

4.1. Procedures performed to obtain data

In this step, the procedures for obtaining data for the study, the equipment used (see Figure 6 to 10) and the calculations performed to obtain the results are presented.

The carrying out of experimental activities has the following objectives:

a) The torque (brake power) of the turbine using a dynamometer, as shown in Figure 6a.

b) The real power of the turbine per m² of mud area for different wind speeds, for this purpose, an anemometer was used to measure the wind speed that can be modified by varying the fan rotation speed by means of a frequency inverter. A wind speed calibration was performed as a function of the engine rotation speed. The torque was measured using a torque meter built for this purpose, which consists of a piece of equipment made up of a leather tape that exerts a frictional force on the wheel connected to the turbine shaft, therefore measuring the force on both sides with a dynamometer determining the friction force, which is expressed as: $F_{atr} = F_2 - F_1$; where the product resulting from the force in question and the wheel radius configures the torque, which is expressed as: $T = F_{atr} \times R$. Then, the rotor rotation speeds (ω) and the developed power were simultaneously measured, which is expressed in $W_{mec} = T\omega$.

c) Determination of the specific speed of the turbine for different wind speeds, with the information obtained from ω, v and r, according to Equation 3.

d) Determination of efficiency as a function of specific speed; this presupposes a relation between the theoretical wind power as a function of its speed and the real power.

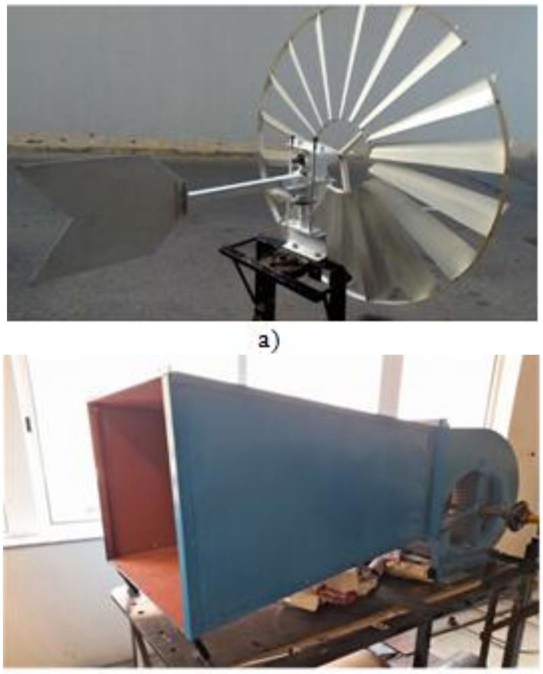

Figure 6: Experimental turbine model; a) multi-bladed turbine and b) wind tunnel.

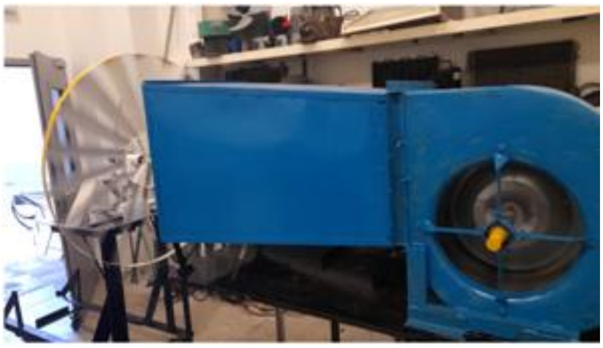

Figure 7: Model of multipass wind turbine and wind tunnel in operation

a) b) c)

Figure 8: Data measurement instrument: a) Digital tachometer-speed (rpm), b) Anemometer-analog wind, and c) Dynamometer-force.

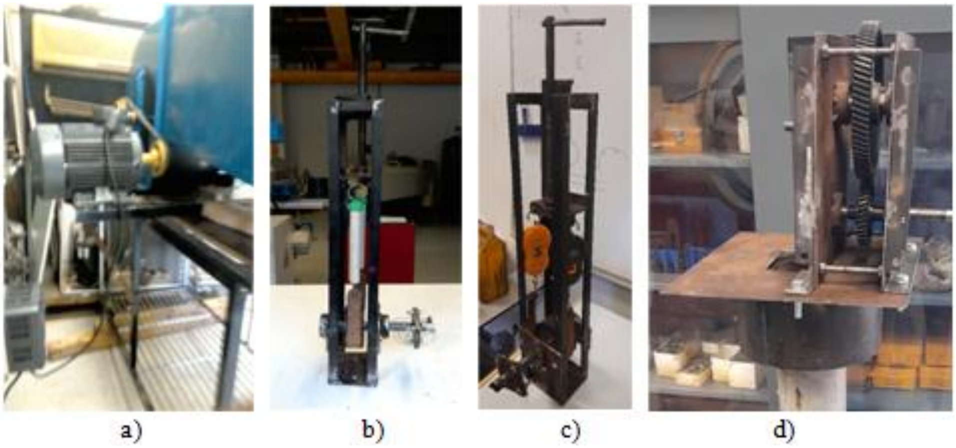

Figure 9: Power measurement equipment developed based on different wind speeds; a) frequency inverter, b) anemometer, c) torque meter, and d) turbine power transmission system.

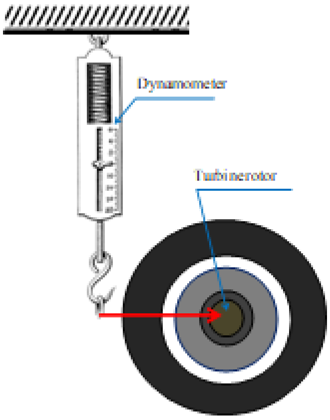

Figure 10: Scheme of the experimental installation to measure the brake power of the multi-blade wind turbine

5. Results and discussion

In view of the results obtained in this research, it is clear and/or demonstrated that the greater the number of blades on the turbines, the easier their operating process will be with lower wind speeds. And in the case of torque, this as well as operation, is greater (torque) when observing a greater number of blades in the turbine.

In the case of a smaller number of blades, these favor speed or agility in the turbines. It is worth noting that the speed in question does not favor an advantageous process to the point of increasing or raising the pumping of water, considering hydraulic piston pumps, since this equipment requires low rotation speeds.

It is important to mention that in relation to the studies carried out, it should be noted that for the experimental conditions considering the speeds from 2 to 7 m/s, the turbine with three blades does not come into operation, that is, they remain continuously at rest in front of the said speeds. In the case of the turbine with 9 blades, it comes into operation when considering only the speeds of 5 to 7 m/s. And in the case of the turbine with 18 blades, it works for all speeds considered in this research, as illustrated in Table 1 of experimental results, and depicted in Figure 11.

Table 1: Results were obtained with different numbers of blades.

N° of blade	V_L (m/s)	ω (rpm)	T (N. m)	N° of blade	V_L (m/s)	ω (rpm)	T (N. m)	N° of blade	V_L (m/s)	ω (rpm)	T (N. m)
3	2	0, 00	0, 00	9	2	0, 00	0, 00	18	2	34, 225	0, 155
	3	0, 00	0, 00		3	0, 00	0, 00		3	64, 230	0, 280
	4	0, 00	0, 00		4	0, 00	0, 00		4	90, 60	0, 740
	5	0, 00	0, 00		5	171, 47	0, 8135		5	124, 53	1, 1125
	6	0, 00	0, 00		6	252, 06	0, 7005		6	139, 33	1, 695
	7	0, 00	0, 00		7	280, 84	0, 985		7	164, 69	2, 195

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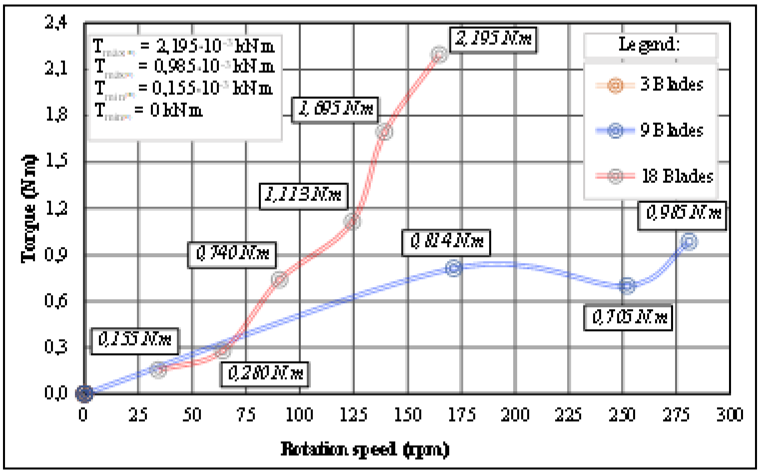

Figure 11: Results were obtained based on the variation in the number of blades.

Based on the results obtained, it is understood that it is recommended to consider the largest number of blades in the process and/or experimental analysis (which in this case is 18 blades). Thus, after this understanding, in the other experiments, 18 blades will be considered in a fixed way. In Table 2 shows the results obtained based on the angle of 30, 45, and 60 degrees.

Table 2: Results were obtained with different numbers of blades.

Speed	For 30 degree (18 blades)			For 45 degree (18 blades)			For 60 degree (18 blades)		
(m/s)	ω (rpm)	T (N. m)	T_{in} (N. m)	ω (rpm)	T(N. m)	T_{in}(N. m)	ω (rpm)	T(N. m)	T_{in} (N. m)
2	0	0	0	30, 2	0, 251	0, 075	34, 23	0, 155	0, 067
3	20, 69	0, 313	0, 102	39, 8	0, 52	0, 103	64, 23	0, 28	0, 106
4	34, 28	0, 778	0, 199	63, 3	0, 905	0, 177	90, 6	0, 74	0, 16
5	45, 89	1, 398	0, 266	83, 3	1, 728	0, 228	124, 5	1, 113	0, 192
6	59, 6	2, 34	0, 342	99, 3	2, 073	0, 307	139, 3	1, 695	0, 202
7	74, 44	3, 378	0, 429	115	3, 225	0, 425	164, 7	2, 195	0, 249

With regard to the use of different angles of attack, considering the turbine, however without the incidence of load, it was possible to show the highest torque at the lowest rotation speed for an angle of 30 degree, and the lowest torque at the highest rotation speed for an angle blade inclination of 60 degree, which is inversely proportional when compared with the first case which corresponds to an angle of 30 degree. In this context, for the operation of the turbine with a blade inclination of 30 degree, a minimum speed of 3 m/s is necessary, in order to produce, consequently, a maximum power. And in the case of the turbine with an angle of 45 degree with a speed of 7 m/s, the results in terms of torque in the domain of rotational speed are graphically presented in Figure 12 e 13.

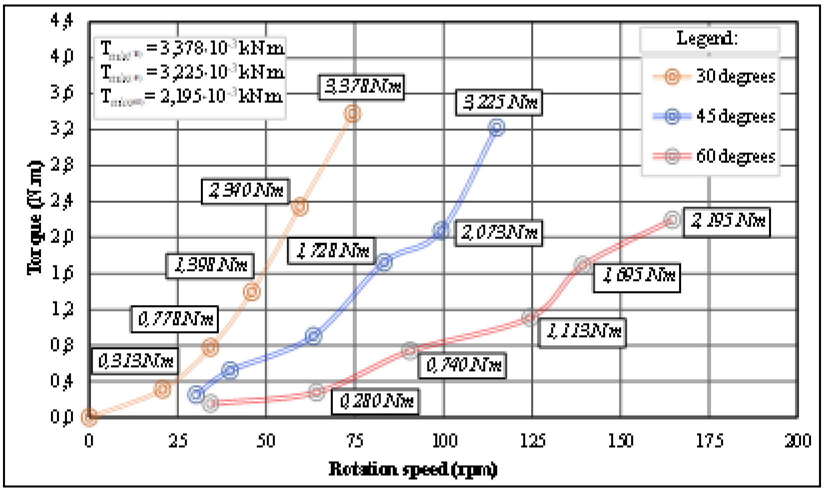

Figure 12: Torque as a function of wind speed for different angles of attack

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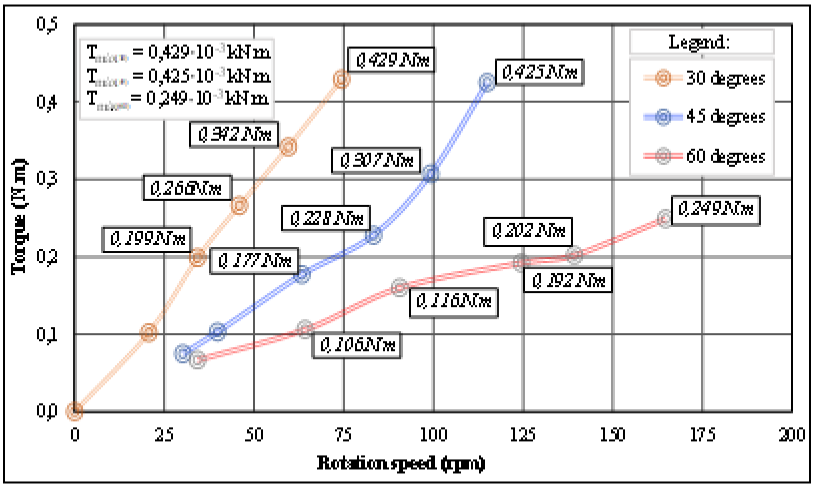

Figure 13: Torque as a function of wind speed for different angles of attack

As can be seen in Table 3 and Figure 14, the best use of wind energy is realized for an angle of attack of the wind on the blades at 45degrees in the range of wind speeds from 2 to 3 m/s. It should be noted that the aforementioned range corresponds to the speed range at which the turbine must operate most of the time during the year. The maximum efficiency in the process of capture and conversion of wind energy was 21.65% considering the angle of 45 degree and wind speed of 5 m/s.

Table 3: Results of actual use of wind energy converted into turbine mechanical energy.

Speed (m/s)	Efficiency (30 degree)	Efficiency (45 degree)	Efficiency (60 degree)
2	0, 00	0, 177738	0, 124776
3	0, 045013	0, 144215	0, 125199
4	0, 078289	0, 168163	0, 196942
5	0, 096455	0, 216522	0, 208364
6	0, 121388	0, 17916	0, 205549
7	0, 137805	0, 202392	0, 198137

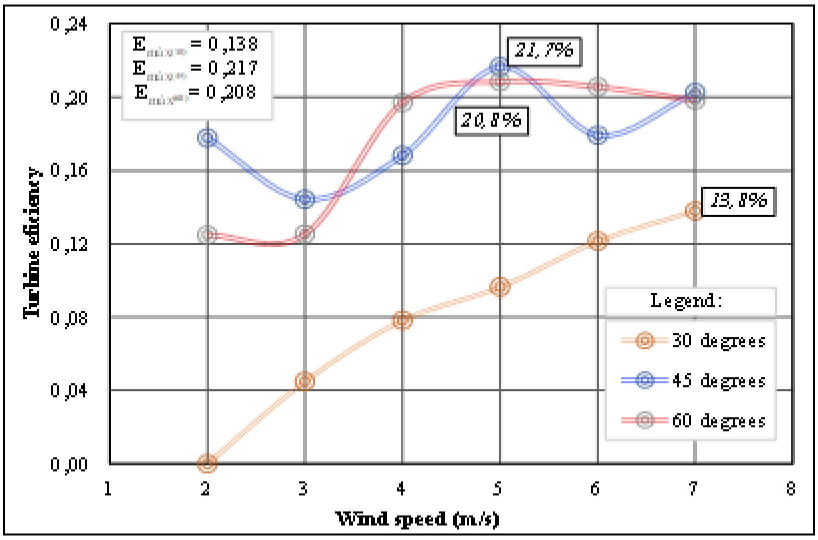

Figure 14: Results related to the efficiency of the multibladed turbine.

It is worth noting that, for this wind speed (5 m/s), the turbine rotation speed is 83.34 rpm, which corresponds to 1, 389 rps, which represents a specific speed of 0.977 described in Table 4. Next, they are presented in table in question and Figure 14, the power values obtained from the turbine taking into account the different angles of attack and wind speeds. Thus, it can be seen that for the angle of 30 degree, the turbine works only with a speed of 3 m/s. It can also be observed that we obtained a maximum power of 38.669 W, obtained with an angle of 45 degree.

Table 4: Coefficient of harnessing wind power as a function of the speed for a 45 degree

Utilization coefficient for the 45o angle of attack					
Speed (m/s)	ω (rpm)	ω (rps)	V_{lin} (m/s)	λ	C_p
2	30, 20	0, 503	1, 77	0, 885	0, 1777
3	39, 83	0, 664	2, 336	0, 779	0, 1444
4	63, 29	1, 055	3, 712	0, 928	0, 1682
5	83, 34	1, 389	4, 887	0, 977	0, 2165
6	99, 32	1, 655	5, 823	0, 971	0, 1792
7	114, 50	1, 908	6, 713	0, 959	0, 2024

As shown in the tables and graphs above, one can clearly observe the differences in terms of angle variation, and realize that the 45 degrees contain the characteristic parameters of the turbine that adapts to the endogenous conditions of the site for the real sizing of a plant pilot project for pumping water at the deep Kilunda farm, in the municipality of Dande, in the province of Bengo (Angola). Next, the results are presented in Table 5 in the form of a percentage difference in efficiency in order to emphasize the previous approaches.

Table 5: Percent difference in efficiency as a function of attack angles.

Efficiency percentage difference (%)		
Turbine with 30and 45 degrees	Turbine with 30 and 60 degrees	Turbine with 45and 60degrees
100, 00	100, 00	42, 45
220, 39	178, 14	15, 19
114, 80	151, 56	17, 11
124, 48	116, 02	3, 92
47, 59	69, 33	14, 73
46, 87	43, 78	2, 15

6. Conclusions

In this research work, an experimental laboratory analysis of the technical characteristics of a mechanical prototype of a multi-blade wind turbine is carried out, for the design of a pilot plant for pumping water in large rural properties, taking into account the variation in wind speed, as well as the variation of the angle of attack. However, in view of the above regarding the simulation process/analyses and experimental evaluations carried out, the following conclusions are drawn:

- The minimum speed for starting and/or running the 18-bladed turbine was determined to be 2 m/s, at which the turbine in question operates to the point of providing certain loads for pumping water;
- With a maximum speed of 5 m/s, taking into account the number of blades, with an angle of attack of 45 degree for each blade, the maximum efficiency of the wind turbine was determined, resulting in 21.65%, at a rotation speed of 83.34 rpm, which corresponds to 1.389 rps, which represents a specific speed of 0.977 m/s;
- In view of the study process, it was possible to prove the technical viability of using this type of technology for pumping water in the selected rural area that has a wind potential and average speeds above 3 m/s, which can contribute to the sustainability of agricultural and livestock projects.
- With the results achieved in this research, it can be said that this study points to new ways of optimizing to enhance and/or contribute to socioeconomic development, with regard to water distribution, all of this, in the most varied existing farms in Angola, especially in the northern provinces of the country, particularly in Bengo.
- It should be noted that the water pumping turbine system has an adequate cost-benefit ratio in terms of easy-to-acquire project needs.
- However, the results achieved served as a basis for studies related to dimensioning and/or technical characteristics of the prototype multi-bladed turbine, for pilot plants for pumping water (in this case, on the Kilunda Deep Farm, located in the municipality of Dande, 90 km from the center of Luanda, in the province of Bengo).

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