Design of a vertical axis wind turbine for pedagogical purpose using solidworks CAD

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Abstract. This project was based on the design and simulation of a vertical axis wind turbine for pedagogical purposes. It must operate at low speeds without the implementation of expensive technology. In order to achieve this, the V methodology was used because it provides a practical tool for the development of projects, allowing the researcher to carry out the integration of the three subsystems of mechatronics engineering: mechanics, electronics, and computer. The final design of the wind turbine has a rotation diameter of 1.2 m and a 2.4 m height and an average flow of 1.5 m/s.

1. Introduction

Wind energy has been used throughout human history, and nowadays, within renewable energy sources. It is experiencing unprecedented growth due to competitive costs and the enormous technological advances achieved in turbines. Although technologically speaking, wind energy has evolved strongly, pedagogically, no laboratory practices have been implemented with wind turbines due to the high cost they represent. A design proposal will be presented to solve this problem [1] with a low-power wind turbine. This device does not need wind guidance for its operation, based on a Savonius type rotor's design.

2. Theoretical framework

2.1. Types of wind turbines

There are two types of Wind turbines, lift and drag. The election depends on which wind-generated force is used [2]. The turbines most widespread today are the ones of lift. The wind drag turbines circulate on both sides of the shovel. These have different geometric profiles. This drag turbine creates an area of depression on the upper face relative to the pressure on the lower face [3]. This pressure difference is called aerodynamic lift and is somewhat like what happens in aircraft wings [4].

Depending on the technology used for the construction of wind turbines can be divided into two large families.

The Savonius type model is the simplest of wind turbines; this consists of 2 or 4 vertical sheets, without a wing profile and curved in the shape of a half-cylinder [5]. The difference in resistance generates the torque on the shaft. This resistance surfaces arranged symmetrically concerning the shaft offer to the wind [6]. This wind turbine requires low power, low efficiency, needs speed control, a mechanical brake, and a little noisy. Today, the most used wind turbine design in wind power generation facilities is the three blades' propeller type. It is necessary to know each of the parts of which it is composed and see its function. Initially, the rotor will be studied [7].
The rotor is an essential part of wind turbines. Because it is responsible for transforming the wind's kinetic energy into a torque moment, which transforms into electricity through precise mechanisms [8], the rotor can have a diameter of 1 meter up to 100 meters. These do not usually have high turning speeds as they depend on the speed at the shovel's tip. The speed is subject to other acoustic criteria. [9] The praises are the ones that support the force coming from the wind, so they are considered the essential part of the wind turbine. These transform the wind's linear movement into rotational and then transmit that movement to the rotor shaft and then generate electrical energy. [10] The generator is responsible for transforming the kinetic energy of rotation into electrical energy from the wind turbine shaft. [11] According to Hualpa (2011), three main types of generators, squirrel cage induction generator, two-phase induction generator, and synchronous generator. [12]

2.2. Design parameters

Different factors that affect the wind turbine's performance must be considered for a wind turbine's design. [13] Once the design power and rated speed were done, the rotor size must be determined, setting the geometric and operating parameters. The use of air density equation is needed:

\[ \rho = \frac{P}{R \sigma} \]  

Equation 1

P is the pressure in pascals, R is the specific constant of gases and T's temperature. The power delivered by the wind meets equation 2:

\[ P_v = \frac{1}{2} A \rho v^3 \]  

Equation 2

A is the rotor area expressed in m\(^2\), the density expressed in kg/m\(^3\), and v the speed expressed in m. Then, the power of the wind turbine depends on the power coefficient of the wind turbine, and equation 3:

\[ P_{aero} = C_p P_v = C_p \frac{1}{2} A \rho v^3 \]  

Equation 3

The final power obtained depends on the yields of both the electric generator and the transmission system. Because of this, the final expression for electrical power is equation 4:

\[ P_{elect} = \eta_m \eta_{ele} P_{aero} = \eta_m \eta_{ele} C_p \frac{1}{2} A \rho v^3 \]  

Equation 4

So, the area needed to produce such power is given by equation 5:

\[ A = \frac{2P_{elect}}{\eta_m \eta_{ele} C_p A \rho v^3} \]  

Equation 5

The design of the labs is taken as a reference to the Model of Lenz. This design is based on the Model Savonius. Lenz's model is based on the Venturi effect, which is explained by Bernoulli's principle. This effect is that a moving fluid goes through a narrowing, its speed increases, and its pressure decreases [14]. For the power transmission can be used the belts, these base their operation on the friction forces. The belt system is a set of two pulleys located at a certain distance and coupled by a belt [15]. There are two types of systems that depend on the pulleys' size: pulley reducing system and speed multiplier system. [16] In the case of a wind turbine, the user is the speed multiplier; in this, the output pulley rotates at a higher speed than the inlet pulley or drive pulley. The following equation 6 defines the relationship between the two pulleys:

\[ i = \frac{n_2}{n_1} = \frac{D_1}{D_2} \]  

Equation 6

Where \( n_2 \) is the speed of the input pulley, \( n_1 \) the speed of the output pulley, \( D_1 \) the diameter of the inlet pulley and \( D_2 \) the diameter of the output pulley.

3. Methodology

This project has been considered a quantitative approach. Because numerical values were analyzed that directly influenced the wind turbine parts' design, as Hernandez (2001) described, they are performing different procedures to identify a solution by analyzing. Subsequently, allowing to perform simulation tests and obtain sustained solutions. The system design will be the dependent variable, and the independent variables are those variables that directly affect the design of our system. For this research project, the V methodology is used. It provides a practical tool for project development,
allowing the researcher to integrate the three engineering subsystems into mechatronics: mechanics, electronics, and programming.

4. Results

4.1. Stage 1: level of cycle A systems
For the mechanical system were considered the different factors affecting the wind turbine. These factors are shown in Table 1.

| Table 1. Environmental conditions in the city of San Pedro Sula |
|---------------------------------------------------------------|
| Altitude above sea level                                      | 83 m.s.n.m |
| Air density                                                   | 1.14 Kg/m³ |
| Average annual speed                                          | 1.5 m/s    |

The rotor consists of two blades with their respective circular caps on each pole of the blades. These are aluminum because this is a lightweight material and because it is highly malleable. The power coefficient of the wind turbine has been considered for the design of the blades. In the case of simpler Savonius wind turbines, the blades consist of two hollow semi-cylindrical parts. However, this design contains a power coefficient of the wind turbine that is very low. Therefore the power that can be extracted from it is minimal. The main shaft is supported by the clamping structure by an axial bearing. In this way, it is possible to make the shaft cantilevered and easy to reach for maintenance.

A voltage inverter was designed to convert 12 V.D.C to 120 V.A.C with a stable frequency of 60 Hz in the electronics part. It should be noted that the output waveform is square. On the other hand, a battery charge meter was designed; this consists of four voltage comparators.

For the programming part, a C code developed in MikroC Pro for Pic was implemented, exclusively for the PIC18F45K22. This code consists of the parts needed to visually display on an LCD the battery voltage and inputs needed to collect the current-voltage information.

4.2. Stage 2: level of cycle A subsystems
In phase 2 of cycle A, the calculations necessary for the wind turbine design were performed. The different components necessary for the design of the cards exposed in the previous stage were listed. It should be noted that the programming system consists of a linear logic, where the input of the microcontroller only represents its value and does not analyze it.

4.2.1 Mechanical system
Initially, wind power is calculated. The power extracted from the wind turbine depends on its power coefficient. The final power achieved by the wind turbine also depends on the performances of the electric generator and transmission system. So, the final expression to calculate the electrical power is equation (4).

It should be noted that the speed data was taken from Galicia in Spain because the speed averages in San Pedro Sula are only predictions. Galicia was chosen because of its resemblance to San Pedro Sula in terms of the weather. Equation 7 gives the area needed to produce a power of 20 W.

\[
A = \frac{2P_{elec}}{C_p \eta_g \eta_f \rho v^3} = \frac{2 \times 20}{0.21 \times 0.95 \times 0.95 \times 1.14 \times 4.21} = 2.89 \text{m}^2
\] (7)

In the case of Savonius-type rotors, the representation area by A-HD. Also, empirical tests are known to be H-2D, so the dimensions of the rotor are as follows:

\[
D = 1.2 \text{ m} \quad \& \quad H = 2.4 \text{ m}
\]

The following equation is used to determine the rotation speed of the rotor in equation 8:

\[
\lambda = \frac{\omega R}{v}
\] (8)

Where the specified speed is (tangential speed/wind speed). The angular velocity (rad/s), R is the radius of the rotor (m), and v the wind design speed (m/s). In the case of Savonius type rotors, the specific speed at which it achieves maximum power has a value of around 0.8. design speed and radius were calculated. So, the resulting angular velocity is shown in equation 9:
\( \omega = \frac{0.8 \times 4}{0.6} = 5.33 \text{ rad/s} \) \( \rightarrow \) \( n = 50.89 \text{ rpm} \approx 51 \text{ rpm} \) \hfill (9)

Several expressions necessary for the design of the electric generator are considered to perform the calculation and sizing of the electric generator. It is known that the equivalent circuit of a generator that is permanent magnets and that the windings are in the stator, is reflected by the following equation 10:

\[ V = E - I (R + X_j) \] \hfill (10)

\( V \) is the voltage in the battery terminals, \( E \) the electromotive force in open circuit, \( I \) the current circulating through the circuit, \( R \) the circuit resistance, and \( X \) the winding reactance. The electric generator was designed to power a 12 V battery, so equation ten must ensure that the voltage is always 12 V or higher. It is considered an electromotive force of \( E = 20 \text{ V} \). Consider that the conductor's data selection and the number of coils to be contained in each winding. First, the number of generator poles was selected, since it is a synchronous generator, the following equation 11:

\[ n = \frac{60f}{P} \] \hfill (11)

Where \( n \) is the rotation speed (rpm), \( f \) the frequency (Hz), and \( P \) the number of pairs of poles. The speed value was calculated, is 51 rpm. In this way the number of pairs of poles is as follows equation 12:

\[ P = \frac{60 \times 60}{51} = 70 \] \hfill (12)

However, 70 pairs of poles are too many, which would lead to enormous generator dimensions. Because of this, a transmission system was integrated. Consider that to use several pairs of poles of 10. So, the rotation speed of the generator rotor should be:

\[ n = \frac{60 \times 60}{10} = 360 \text{ rpm} \] \hfill (13)

Therefore, the multiplication ratio is as follows:

\[ i = \frac{360}{51} = 7 \]

Now the number of coils must be determined. Consider that to use three coils per phase. These coils lead to having a three-phase system and contains a total of 9 coils in the stator. These coils connected in series, so between the three coils per phase, there is \( E = 20 \text{ V} \). On the other hand, the magnets are selected because the generator is from permanent magnets. Circular neodymium-shaped magnets with diameters of 30 mm were selected, being one of the most economical on the market. These magnets create a 1.2T magnetic field. Then the authors proceed to select the conductor, consider the desired power, and the voltage of the battery terminals. The current calculation is shown in equation 14.

\[ I = \frac{P}{V} = \frac{20}{18} = 1.1 A \] \hfill (14)

Considering that, thanks to the generator's design, it is sufficiently cooled, it is considered a current density. Because of this, the following equation 15 was considered in support of the current intensity in the conductor: \( 1A/mm^2 \). The conductor selected considering are shown in Table 2.

\[ A = \frac{I}{j} = \frac{1.1}{1} = 1.1mm^2 \] \hfill (15)

| A.W.G. number | Diameter (mm) | Section \((mm^2)\) | Resistance \((s/km)\) \(\Omega\) |
|----------------|---------------|-------------------|--------------------------|
| 16             | 1.291         | 1.31              | 13.17                    |

Table 2. Selected driver features

Once the conductor is established, the authors proceed with coils calculation. For this calculation the equation 16 refers to the electromotive force of each coil is used:

\[ E = 4.44 \times N \times f \times B \times A \] \hfill (16)
E is the induced fem in each coil, N the number of coils per coil, f the frequency, B the magnets' magnetic field, and A is the magnetic area. In this case, the magnetic area is induced by magnets. This results as follows:

$$\frac{20}{3} = 4.44 \times N \times 60 \times 1.2 \times \pi \left(\frac{0.03}{2}\right)^2 \rightarrow N = 29 \text{ espiras}$$

To have a safety factor, consider using 30 coils. Therefore, these coil coils are arranged in a rectangular shape distributed in 6 rows and five columns. Due to the stator design, the first-row winding has dimensions of 40x2 mm.

To verify that the generator works as expected, the final voltage must be met. This is verified using equation 34. Initially, the resistance of each coil must be calculated in equation 17:

$$R = \frac{1.317\Omega}{km} \times \frac{1km}{1000m} \times 3.2m = 0.042\Omega$$

The following equation is considered to know the value of the reactance:

$$X = 2\pi f L$$

Where f is the frequency, and L is the magnetic inductance. The following expression is presented for the magnetic inductance of the generator:

$$L = 1.257\mu \times \frac{N^2 S}{10^8 L_a}$$

In this case, the relative magnetic permeability of the vacuum is one, and a total of 30 coils are available. To perform the spiral section calculation, the section of an average coil must be taken. Therefore, the section will be represented by the following expression:

$$S = (40 + 5 \times 1.291) \times (2 + 5 \times 1.291) = 3.93 \text{ cm}^2$$

The length of the coil is:

$$L_a = 6 \times 1.291 = 7.746 \text{ cm}$$

Therefore, the inductance value is as follows:

$$L = 1.257 \times 1 \times \frac{30^2 \times 3.93}{10^8 \times 0.7746} = 4.56 \times 10^{-5} \text{ H}$$

$$X = 2\pi \times 60 \times 4.56 \times 10^{-5} = 17.21 \text{ m}\Omega$$

$$V = \frac{20}{3} - 1.1(0.042 + 0.01721j) = 6.60 \text{ V} > \frac{12}{3}$$

4.2.2 Electronic system

As discussed in the previous stage, the electronic system consists of 2 cards with different applications. The first is to reverse the 12 VDCs from the battery to 120 VAC. Table 3 shows the electronic board components.

| Table 3. Inverter card components |
|----------------------------------|
| Component                        | Value   | Amount |
| 100KΩ                            | 1       |
| Resistance                       | 10KΩ    | 1      |
| Ceramic capacitor                | 100nf   | 4      |
| Timer                            | NE555   | 1      |
| Flip Flop                        | 74LS73  | 1      |
| Voltage regulator                | 7805    | 1      |
| Transistor                       | TIP122  | 2      |
| Diode                            | 2N3055  | 2      |
| Transformer                      | LP-577  | 1      |

The inverter card's idea is that it converts the 12 VDC to 120 VAC with a frequency of 60 Hz. In the next stage, the design will be displayed and how it works. The card to measure the battery charge requires one integrated circuit. Stage 3 of this cycle will illustrate the two ways of forming the circuit. Table 4 shows the components for the second development board.
Table 4 Voltage meter components

| Component                        | Value  | Amount |
|----------------------------------|--------|--------|
| Resistance                       | $680Ω  | 3      |
|                                  | 10K    | 1      |
|                                  | 1.2K   | 1      |
|                                  | 15K    | 1      |
|                                  | 1K     | 4      |
| Integrated circuit or            | LM324  | 1      |
| amplifier operations             |        |        |
| Diode                            | Zener 5.1V | 1   |
| Led Diodes                       | X      | 4      |
| Potentiometer                    | 10KΩ   | 1      |
| Pic                              | 18F45K22 | 1  |

4.2.3 Programming system

For the code's writing for the load measurement, the necessary ports are established on the microcontroller, being the unique RB0-RB6 for using the LCD and RD0-RD3 ports the ports selected for the load measurement inputs.

4.3 Stage 3: performing parts of cycle A

4.3.1 Mechanical system

Initially, the wing's profiles' design was carried out for shaft design that joins the wind turbine rotor with the transmission system. A design was made that can be screwed by a sheet of steel to the lower circular cap to rotate together with the rotor. In addition, the bottom of the shaft was designed with flat faces so that it can be attached to the large pulley of the transmission system. The stander was designed to be the fixed part of the generator for easy manufacturing. A.B.S. disc was designed to be printed in 3D. The caps are two circular steel plates with a thickness of 5 millimeters to prevent possible deformations. The large pulley has a total diameter of 360 mm. This value is taken from the calculations performed in the previous stage with the help of equation 36. The small pulley, on the other hand, has a total diameter of 51 mm. Both pulleys feature the groove for a 13 mm thick band. Both pulleys were designed to meet the ratio of i-7.

4.3.2 Electrical system

The inverter card is capable of transforming 12V. D. C to 120 V. A. C, this using some elements such as the TIP122, these are responsible for activating the 2N3055 power transistor. The oscillation is delivered by the integrated circuit NE555. In contrast, the TIP122 transistors are activated by the flip flop 74LS73, which maintains a constant oscillation of 60 Hz and precise by its rise flank.

4.3.3 Computer system

For the software part, a code was written in Mikroelektronika MikroC PRO for the P.I.C. program. This code was developed for the PIC18F45K22 microcontroller. It has the necessary outputs to manipulate an LCD screen and display the card's data to measure the battery charge level.

4.4 Stage 4: integration of parts of cycle A

The final rotor design has a diameter of 1.2 m and a height of 2.4 m. The rotor's top disc must be bolted to the shaft, which is attached to the small pulley of the transmission system. Stage 5: integration of cycle A subsystems. Figure 1 shows how the wind turbine absorbs wind speed. It is higher when it hits the structure and is almost 0 when passing the prototype, thus generating a zero-wind return.
Figure 1. Airspeed lines as air pass through the wind turbine
Source: Own (2020).

Figure 2 perceives a cut of the airflow passing through the wind turbine. It is possible to visualize that the objective of the design is met. Because the air return that generates a force against the turning direction is almost 0, being null.

Figure 2. Cut view of the airflow in the wind turbine
Source: Own (2020).

4.5 Stage 6: results of the final prototype of cycle A
The wind turbine design meets the set milestones, absorbing as much wind energy as possible and canceling the wind return to cause wind turbine braking. On the other hand, the electric generator capable of generating 20 W of power was designed to charge a 12 V battery and design two electronic cards, one to reverse the D.C. voltage coming from the battery to A.C. voltage and another card to measure the battery charge.

5. Conclusions
The information needed for the design of the wind turbine is collected, an average flow of 1.5 m/s, according to NASA MERRA-2 statistics. However, data from the Galician wind farm "Sotavento"
were used to design the wind turbine because its data is real. The final dimensions of the wind turbine are 1.2 m in diameter and 2.4 m in height. A Savonius-type profile has been defined for the wind turbine design. It does not need wind guidance for its operation. It is not necessary to implement other equipment to generate the initial start of the wind turbine. The wind turbine has complied with the set milestones, absorbing as much wind. Thus, increasing the rotation speed of the rotor and with this the generation of electric power.

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