A Levitating Frictionless_Vertical Windmill

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Abstract

To harness wind energy in low wind speed areas, a vertical axis wind turbine (VAWT) is generally more suitable than a horizontal axis wind turbine. To improve the feasibility of using a VAWT, a magnetic levitation bearing concept, utilizing neodymium magnets, is used to make the bearing frictionless. A new experimental type of airfoil called EN0005 is used that boasts better self-starting ability than conventional airfoils. The design parameters of the wind turbine are explored and reviewed to create a final design that is modelled in SolidWorks. This final design is then put through simulations and analysis in ANSYS FLUENT before being fabricated as a prototype. This final prototype produces similar results to other findings and validates the report. The EN0005 blade profile appears to improve the self-starting capability of the wind turbine and improve viability of Darrieus turbines in lower wind speeds. These findings verify the benefits of using a magnetic frictionless bearing for wind turbines.

Keywords: Vertical axis wind turbine; Magnetic bearings; Darrieus; Wind energy

1. Introduction

Climate change is one of the most pressing issues of the current generation. Since the beginning of the 21st century, it has been scientific consensus that human activity has been the major factor in climate change, however efforts and policies to reduce the effect of these activities have either made little or no impact[1]. In 2017, carbon dioxide emissions related to energy generation have increased by 1.4%, after 3 years of previously remaining stagnant. According to the International Energy Agency, generation of energy is one of the largest contributors to climate change, accounting for 80% of carbon dioxide emissions and two-thirds of greenhouse gas[2]. Therefore, to combat climate change, there must be a huge shift in the energy sector. This would involve searching for alternative energy sources that are renewable. One potential energy source that has not fully been explored is wind.

There are two configurations of vertical axis wind turbines, horizontal axis wind turbines (HAWT) and vertical axis wind turbines (VAWT). HAWTs have shafts that are parallel to the direction of wind flow and the ground, while VAWTs have shafts that are perpendicular to the wind flow and ground. The concept of HAWTs have been used since 5000BC and are more widely used in large scale operations, due to several factors. It has received much more funding and research than VAWTs and currently has a greater efficiency than VAWTs, due to its ability to face the wind and obtain maximum wind energy when facing the wind. However, HAWTs would not be able to work in areas that have inconsistent wind direction. VAWTs, on the other hand, are omni directional and perform better at lower wind speed areas but perform worse in high-speed areas. VAWTs can also backtrack as the blades also need to move toward the wind direction which will add resistance[3].

Compared to HAWTs, VAWTs are currently less researched and less developed as a technology[4]. It is generally known that VAWTs are more feasible for low wind speed areas with sporadic wind direction. However, VAWTs are still not widely used in areas with these conditions. With greater research and development, it could become the new energy solution for these areas.

Additionally, VAWTs can be utilized in rural areas not connected to power grids, due to its generally more compact design compared to HAWTs.

An interesting engineering problem of VAWTs that can be explored is the friction caused between the rotation of the turbines and the bearings on the shaft. A potential solution to this is using magnetic bearings to "levitate" the turbine to create a nearly frictionless connection between the rotor and stator. With close to zero friction, the feasibility of the VAWT could improve and lead to greater investment and research. That possibility, along with other design considerations, will be explored in this report.

2. Methodology and Experimental Setup

This research deals with the design, analysis, and fabrication of a levitating frictionless vertical axis wind turbine. SolidWorks, ANSYS and CFD analysis software's are used in the design. The final product has been fabricated as a prototype and been tested to verify its viability.

2.1. *Design Parameters*

The design parameters of the levitating frictionless VAWT encompasses many parameters[5], but for this research, the key parameters considered are shown in Table 1.

Table 1. Key Parameters

Category	Parameters	Fixed/Variable
Physical Features	1. Blade Shape (Airfoil)	Fixed
	2. Number of Blade (N)	Fixed
	3. Supporting Struts	Fixed
Dimensional	4. Swept Area (A=HD)	Fixed
	5. Solidity (Nc/R)	Fixed
	6. Aspect Ratio (H/c)	Fixed
Operational	7. Rated Power Output (Po)	Variable
	8. Rated Wind Speed (V ∞d)	Variable
	9. Cut-in Speed (Vcut-in)	Variable
	10. Cut-out Speed (Vcut-out)	Fixed
	11. Power Coefficient (CPd)	Variable
	12. Tip Speed Ratio (λd)	Variable
	13. Rotational Speed (ωd)	Variable
	14. Pitching of Blade (γd)	Fixed
Others	15. Material	Fixed
	16. Magnet	Fixed

The optimal number of blades will differ depending on whether a Savonius or Darrieus turbine is to be chosen. As the literature review has shown, the optimal number of blades for Savonius turbines is two[6], while the optimal number for Darrieus turbines is generally agreed to be three[7, 8].

The selection of magnet is also a factor for the levitating frictionless wind turbine. The higher magnetic strength of the neodymium magnets will generate greater magnetic flux and thus, more electricity[9]. With these factors considered, neodymium magnets are chosen in this research.

2.2. *Design Selection*

The configuration in Fig. 1, is showing the stator as a stationary base of the turbine. The rotor, blades, and supporting struts are being held up by the pair of magnetic bearings in between the stator and rotor. As shown, the struts and rotor make no contact with the stator or the shaft, in the try of making it frictionless.

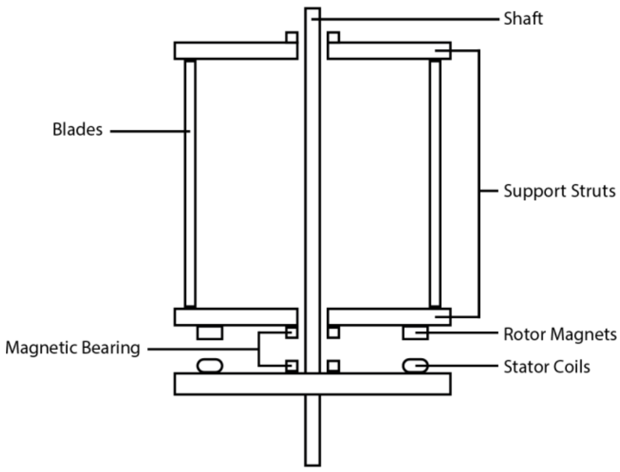


Fig. 1 Configuration of magnets, blades, rotors, stators, and shaft in design

2.2.1. *Blade Profile Selection*

Considering a Darrieus wind turbine, a selection is needed for a blade airfoil. The three airfoils that were considered were the NACA0018 airfoil, which is one of the most common airfoils used currently, and two experimental airfoils that are recently developed with the purpose of greater self- starting ability, MI-VAWT and EN0005[10, 11]. The strengths and weaknesses of these airfoils are presented in Table 2.

Table 2. Comparison of Blade Airfoils

	NACA0018	**MI-VAWT**	**EN0005**
Strengths	Simple to fabricate.	Good self-staring ability.	Best self-starting ability.
	Well studied and researched by many.	Structurally strong.	Performs at low speeds and high speeds
Weaknesses	Weakest self-starting ability out of all the choices.	More difficult to fabricate. Relatively little research.	More difficult to fabricate. Less research than NACA0018, but greater amount of research than MI-VAWT.

MI-VAWT can perform well, but has less self-starting ability, and it has a more similar shape to NACA0018, so it may be difficult to precisely fabricate it. However, it does have a simpler shape than EN0005, therefore it will be less difficult to fabricate compared to EN0005. Despite this, EN0005 airfoil has superior self-starting ability and performance as EN0005 can self-start at speeds of 1.25m/s[12], which would be around the average wind speeds of Malaysia[13]. So, it is the most suitable airfoil for low wind-speed areas. Therefore, the EN0005 blade profile, as shown in Fig. 2, has been selected.

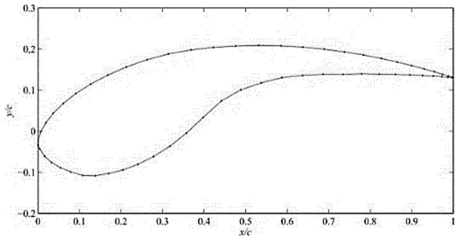


Fig. 2. Blade profile for EN0005

2.2.2. *Dimensional Calculations*

According to the Betz's Limit, the maximum power coefficient is 0.593, but the maximum practical limit is currently around 0.45. For the purposes of this design, a greater wind speed of 6m/s may be used to design the turbine to test the concept of the frictionless levitation. Before calculating the dimensions of the turbine, the values of solidity and aspect ratio must first be fixed. The aspect ratio will be greater than or equal to 7.5[14, 15]. Solidity is preferred to be lower to have greater self-starting capability. Due to this, for the design, solidity will be fixed at the value of 0.5, as several papers have aimed for low solidity when prioritizing self-starting ability and some have values near to 0.5[12]. For purposes of calculating the design, 20 watts of power will be the target power for this small-scale turbine.

To find the optimal swept area of the wind turbine, it is necessary to evaluate the coefficient of power using Eq. (1). The max *Cp* that is in practical use is 0.45. Although, it is to be expected that the *Cp* will not reach this maximum. The turbine designed in this research is considering this value of *Cp* in mind.

$$Coefficient\ of\ power,\ C_p = \frac{P}{P_w} = \frac{P}{\frac{1}{2}\rho A V_\infty^3} \quad (1)$$

Where,
ρ is density of air
A is the swept area of the turbine
$V\infty$ is the velocity of wind
P is the power generated by the turbine

$$C_p = \frac{P}{P_w} = \frac{20}{\frac{1}{2}\left(1.225\frac{kg}{m^3}\right)(6m/s)^3 A} = 0.45$$

A = 0.336 m²

With the value of area determined and the equations of solidity and aspect ratio, the values of diameter, height, and chord length of the turbine are found. These calculations use Eq. (2), Eq. (3), and Eq. (4) [16, 17]. The dimensions found will be the dimensions of the turbine that will be tested.

$$\boldsymbol{Solidity, \sigma = \frac{Nc}{2R},\ where\ N = 3} \quad (2)$$

Where,
N is the number of blades
c is the chord length of the blade H is the height of the blade
R is the radius of the turbine

$\sigma = 1.5c/R = 0.5$
Thus, $\mathbf{R = 3c}$

Aspect ratio, $a = H/c = 7.5$ (3)
Thus, $\mathbf{H = 7.5c}$

Area, A = 2RH (4)
$A = 2(3c)(7.5c)$
Thus, $\boldsymbol{A = 45c^2}$

$\therefore 45c^2 = 0.336m^2$

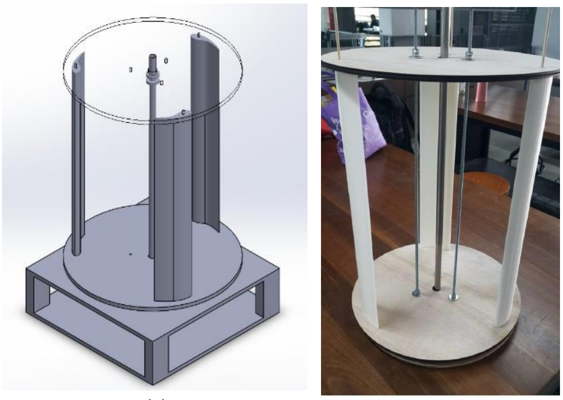
$\therefore$ $\boldsymbol{Chord\ length, c} = 0.0864m = \mathbf{8.64cm}$
$\therefore$ $\boldsymbol{Height, H} = 7.5c = \mathbf{64.8cm}$
$\therefore$ $\boldsymbol{Diameter, D} = 2R = 6c = \mathbf{51.84cm}$

2.2.3 *Final Design*

The final parameters and design selected can be seen in Table 3 and Fig. 3 (a) and (b). The design selected is a Darrieus wind turbine with the EN0005 airfoil. The first reason is that the airfoil EN0005 has a better self-starting ability than the NACA0018 airfoil. Secondly, Darrieus wind turbines are more efficient than Savonius turbines. Thirdly, although it may be the most difficult to fabricate, it would be beneficial to obtain data on this type of turbine and airfoil combination in a Malaysian context. This is important, as the airfoil is a recent development and gaining insight on its feasibility in Malaysia could spark interest to invest further research.

Table 3. Fixed Parameters of Design

Parameter	Options
Airfoil Shape	EN0005
Number of Blades	Three-bladed (Darrieus)
Supporting Struts	Simple
Swept Area	0.336m^2
Solidity	0.5
Aspect Ratio	7.5
Pitching of Blade	0^0
Magnet	Neodymium
Material	Aluminum



(a) (b)
Fig. 3. (a) and (b) Final Selected Design

The axial flux generator consists of the rotor and the stator. The rotor is located on the bottom of the wind turbine, while the stator is located on the top of the base. Due to availability of materials, the axial flux generator consists of 8 neodymium magnets and 6 coils. The ideal ratio of magnet to coil for axial flux generators is 4:3. The magnets are N35 circular magnets of 30mm diameter and 10mm thickness. These magnets are placed around a circle of radius 75mm around the center of the supporting strut.

The stator consists of six coils arranged in a circle of the same radius as the rotor. Coils of 70 turns each are used. The copper coils are soldered together in the arrangement shown in Fig. 4 The stator is connected in a 3-phase star connection.

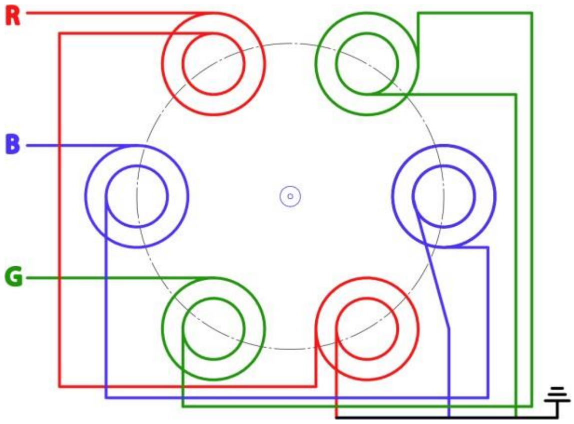


Fig. 4. Stator phase connection diagram

Different colored wires are used to indicate different phases for better organization and ease of modification in the future. The 3 phases are then connected to a 3-phase bridge rectifier to convert the AC voltage produced into DC voltage. The three-phase bridge rectifier was formed using 6 diodes, terminals, and a PCB board. The diodes and terminals were soldered onto the PCB.

3. Results and Discussion

3.1. *Simulation*

ANSYS is used for both the structural simulation and computational fluid dynamic (CFD) simulation to determine its structural stability and its velocity and pressure contours.

3.1.1. *Structural Simulation*

From the results shown in Fig. 5 and Fig. 6, the highest points of stress and strain occurs at the center of the turbine, near the area where the magnet bearings are placed. However, the maximum deformation is only 2.2976 x 10-5 mm which can indicate a very little deformation due to its own weight. Also in the simulation, the factor of safety for the entire body is 15, which is a very large number and indicates that the turbine is very strong. At the same time, it also shows that there may be a possibility to reduce the amount of material on the turbine to reduce its weight and it will still be safe.

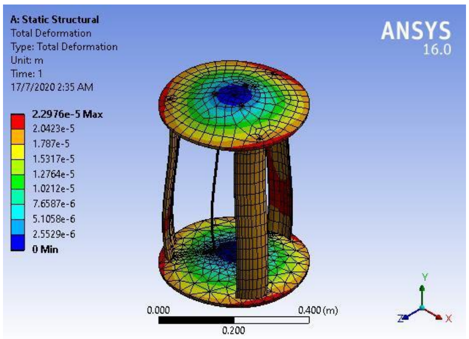


Fig. 5. Total deformation of turbine in ANSYS

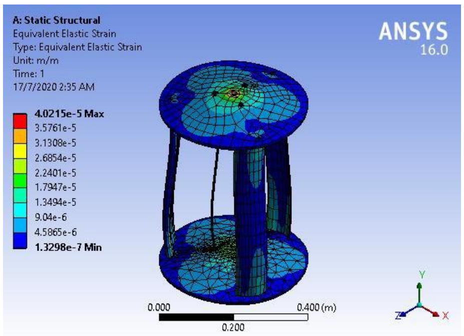


Fig. 6. Equivalent elastic strain of turbine in ANSYS

3.1.2. *CFD Simulation*

Fig. 7 and Fig. 8 are showing the velocity and pressure contour plots, respectively. These plots are generated using wind speeds of 6 m/s as used in previous calculations for the design. Fig. 7 shows a decrease in velocity magnitude from the inlet (upstream) side to the outlet (downstream) side, with a magnitude of 1.171×103 m/s at the upstream blades to 1.673×102 m/s at the downstream blades. This difference in magnitude causes an overall lift in the turbine. Similarly in Fig. 8, there is a decrease in pressure from upstream side of the swept area to the downstream side, from –8.369×104 Pa to –5.1×105 Pa. This drop creates a useful pressure difference across the blades and propels the rotor. There are also even further static pressure drops near the blades, due to the curvature of the EN0005 blades. These circulations drop the pressure as the direction of rotation are opposite to the direction of rotation of the wind turbine and further increase the power produced. From the CFD analysis, it can also be seen that wind energy is extracted by the wind turbine. This can be seen as the velocity magnitude decreases across the rotor as energy extracted from the wind will reduce the velocity.

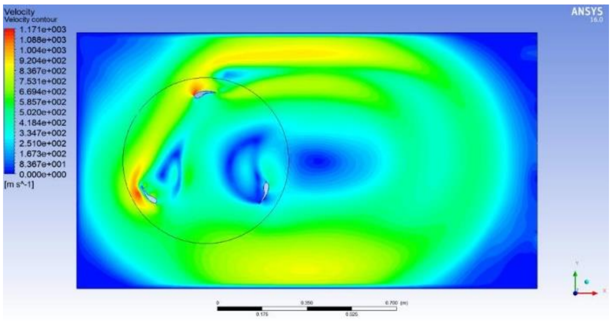


Fig. 7. Velocity contour of 2D wind turbine

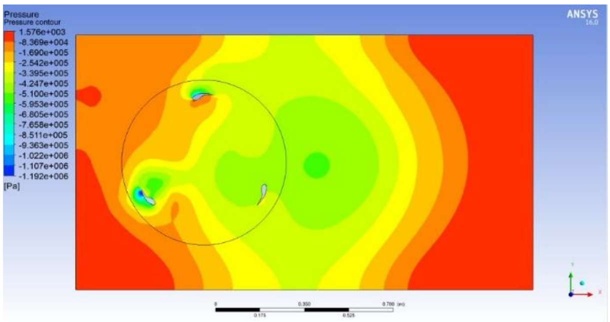


Fig. 8. Pressure contour of 2D wind turbine

3.2. ***Experimental Result***

The wind turbine prototype, as shown in Fig. 9 was tested with a three-phase load of 15Ω resistors for the peak AC voltage and a singular 15Ω resistor for the converted DC voltage at various wind speeds. The voltage and current are measured using multi-meters. The rotational speed is measured by recording video of the turbine and slowing down playback of the video to record the number of rotations within a minute. The results are shown in Table 4 with the wind speeds ranging from 2 to 4.5 m/s in 0.5m/s intervals.

Table 4. Load test results for variable wind speeds

Wind Speed (m/s)	**RPM**	**Peak VAC (mV)**	**VDC (mV)**	**Current (mA)**
4.5	90	90	52	0.25
4	60	85	49	0.23
3.5	35	81	46	0.19
3	20	76	42	0.16
2.5	14	63	35	0.12
2	6	51	30	0.08

Fig. 9. Working prototype

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3.2.1. *Load Test Result*

Table 5 shows the tip speed ratio and power generated at the various wind speeds. The tip speed ratio is calculated from the wind speed, rotational speed, and radius of the turbine as shown in Eq. (5). In Fig. 10, power generated increases as TSR increases. Generally, power generated will peak at a certain TSR value, however due to the low wind speeds being used to test the wind turbine, the peak TSR value may be much higher.

$$Tip\ speed\ ratio\ (TSR),\ \lambda = \omega R / V\infty \qquad (5)$$

Where,
ω is the rotational speed of the turbine in rad/s
R is the radius of the turbine in m (R = 0.1728m)
$V\infty$ is the wind speed in m/s

Table 5. Tip speed ratio and power generated at variable wind speeds and RPM

Wind Speed (m/s)	RPM	Rotational Speed (rad/s)	Tip Speed Ratio	Power (μW)
4.5	90	9.42	0.36	22.5
4	60	6.28	0.27	19.55
3.5	35	3.67	0.18	15.39
3	20	2.09	0.12	12.16
2.5	14	1.47	0.10	7.56
2	6	0.63	0.05	4.08

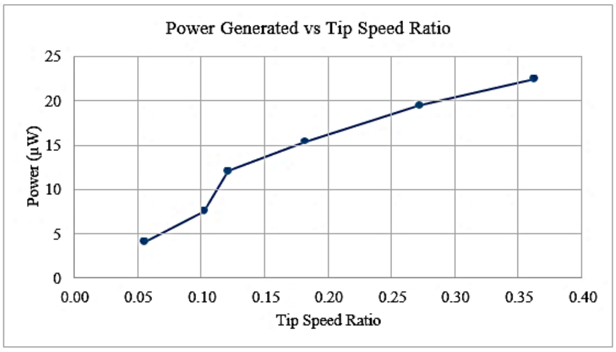

Fig. 10. Graph of Power Generated vs Tip Speed Ratio

4. Conclusion

The vertical axis wind turbine has been designed and constructed. The magnetic levitating bearings, comprised of neodymium ring magnets, are used successfully to reduce the friction and to support the weight of the turbine. In addition to the wind turbine, an axial flux permanent magnet AC generator has been also successfully constructed. The output of this generator was converted to DC using a three-phase bridge rectifier which was also self-constructed. In addition to testing magnetic levitation, the EN0005 blade profile was able to self-start consistently and produce energy at wind speeds as low as 2 m/s, which is not typical of a Darrieus turbine.

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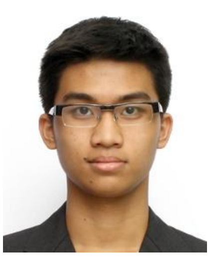

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