The analysis of wind blade on the performance of Vertical Axis Wind Turbine

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Abstract. The long-term energy crisis is one of the biggest issues of this century that needs to be tackled to ensure a prosperous future for coming generations and wind energy is one of the energy sources that grows rapidly and most promising renewable energy. Vertical Axis Wind Turbine (VAWT) is the best option for small wind turbine project and suitable for low average wind speed environment. In this project, experiment had been carried out to study the effect of wind blade number on the Savonius wind turbine performance at different wind speeds and a comparison had been made to choose the best performance between 2, 3, 4, 5 and 6 blades wind turbine. A small Savonius wind turbine prototype, PicoScope, Digital Anemometer, Digital Tachometer and other equipment were used for this purpose. A PicoScope software with a hardware device had been used to create an oscilloscope and spectrum analyser on the PC. The experiment was carried out in an open room space to acquire a close condition to the real environment. The performance results were analysed and Malaysia’s average wind speed had been used as the guideline for the comparison. It can be deduced that 5 blades rotor gives the best performance compared to the 2, 3, 4 and 6 blades rotor. At wind speed 6.1 m/s, 5 blades rotor produced optimum mechanical power output at 260 mW, power coefficient of 0.109 (10.9 %), torque at 0.12 mN.m and tip speed ratio at 8.28.

Keywords. Vertical axis wind turbine; VAWT; Savonius turbine; Wind speed; Number of blades

1. Introduction

The long-term energy crisis is one of the biggest issues of this century that needs to be tackled to ensure a prosperous future for coming generations and wind energy is one of the energy sources that grows rapidly and most promising renewable energy as it economically viable [1]. More of scientific investigation and technical development for exploiting energy from the wind has been increasingly simulated due to the conventional energy sources are limited, global warming resulted from greenhouse gas emissions and environmental pollution. So, more attention and interest have been paid to the utilization of renewable energy source such as Wind Energy, Solar Energy, Hydropower, Geothermal Energy and etc. Wind energy is the kinetic energy stored in the wind which compromises only a small portion of the total energy that reaches the earth [2].

Wind turbines are constructed as part of the strategy to reduce dependence on fossil fuels. Wind turbine is a rotating device which converts the kinetic energy in the wind into mechanical energy around
the rotor. It is then converted into electrical energy through the electric generator that connected with the main shaft where the rotor is attached. What makes wind turbines different from other conventional generation systems, is the fact that the power inflow rate cannot be control; as known wind is, for its nature, a highly unstable and unpredictable source. Thus, even a slight change in the wind speed or direction can cause a sensible and unpredictable difference in the power output of the turbine, in a very short time-frame [3].

In generating wind energy, both Vertical Axis Wind Turbine (VAWT) and the Horizontal Axis Wind Turbines (HAWT) play a significant role. The vertical axis wind turbines have been used widely in a small wind projects and residential wind applications because HAWTs are more difficult to control in strong winds.

In term of comparison between HAWT and VAWT, it had been involved plenty of aspects such as technical, safety and environment. However, in term of mechanical properties, HAWT has the power generation efficiency ranged between 50 – 60 % with the help of high starting wind speed from 2.5 -5.0 m/s and high rotating speed. Although the HAWT’s blade rotation space is quite large, HAWT still has weak wind-resistance capability with the interference of electromagnetic. Whereas, VAWT had showed the power generation efficiency more than 70 % with no electromagnetic interference and low starting wind speed from 1.5 – 3.0 % and rotating speed which required no yaw and pitch controls. Due to its design it has strong wind-resistance capability with typhoon resistance up to 12-14 class [4, 5]. VAWT has low power coefficient, hence, this type of wind turbine is mostly used for wind speed measurements [6, 7].

The advantage of the VAWTs is that the generator is on ground level so they are more accessible [2]. However, because of its proximity to the ground, wind speeds available are lower. One interesting advantage of VAWTs is that the blades can have a constant shape along their length and, unlike HAWTs, there is no need in twisting the blade as every section of the blade is subjected to the same wind speed. This allows an easier design, fabrication and replication of the blade which can influence in a cost reduction which is one of the main reasons to design the wind turbine with this rotor configuration [8].

Despite the advantages, VAWT is not recommended to be utilize widely due to its performance issue and not being able to survive in the market. This is why HAWT is still being the most purchase item and renewable energy construction choice to the buyers and manufacturers. Plus, in the form of theories, calculation and measurement, VAWT performance analysis and studies have different understanding and explanation towards the consideration of the performance variables in most of the general equation. Furthermore, in order to determine the performance of VAWT, it is surprising that its performance variables are not completely independent yet rather interlinked to each other and complicated. However, recently VAWTs have received renewed interest for wind energy harvesting in two new potential locations which are in urban and rural environment and far offshore [9-11].

This paper will be focused on Savonius turbine, one of the VAWT types. The Savonius turbine was first invented in Finland by Sigurd J. Savonius in the year 1920 and patented in the year 1929 [4-5, 12]. The Savonius is a drag-driven machine, consisting of two open half drums attached to a central rotating shaft in opposite direction and the top view of a conventional Savonius rotor looks like an ‘S’ shape. According to Shankar [13] the performance of Savonius turbine was strongly affected by numbers of blades and Blackwell et al., [14] reported that number of stages also play its role in improving the Savonius turbine performance [15].

In general, the performance of vertical axis wind turbine is affected by various factors. The most common factors are the effect of number of blades, the effect of blade profile, the effect of aspect ratio, the effect of surface roughness and the effect of Reynolds number [16-20]

One of the factors affecting the performance of vertical axis wind turbine will be the main focused in this paper.

- An experiment will be conducted to determine the effect of number of blades to the performance of the Savonius wind turbine at different wind speeds.
• The effect of number of blades will be discussed and a comparison will be made to see which
one is better in performance than the others.

2. Performance and mechanical concept of energy

2.1. Kinetic energy and wind power

Wind turbine converts the kinetic energy in the wind into mechanical energy. The total wind power of
the wind stream is equal to the time rate of kinetic energy.

\[ KE = \frac{1}{2} m V^2 \]  

(1)

where \( m \) is the mass in (kg) and \( V \) is the velocity in (m/s).

The mass flow rate of air passing through an area \( A \), where volume flow rate \( \dot{V} = AV \).

\[ \frac{dm}{dt} = \rho AV \]  

(2)

Since, the power in the wind is given by the rate of change of energy,

\[ P_{\text{wind}} = \frac{1}{2} \frac{dm}{dt} V^2 \]  

(3)

Hence, from equation (3), the total wind power can be defined as:

\[ P_{\text{wind}} = \frac{1}{2} \rho AV^3 \]  

(4)

The equation of the swept area, \( A \) is described as:

\[ \text{Swept Area, } A = \pi r H \]  

(5)

where \( r \) is the radius of the blade and \( H \) is the height of the blade. Equation (5) is obtained from the
formula of half cylinder. The equation will be used to calculate the area of each blade rotor number on
the turbine.

2.2. Power coefficient, \( C_p \)

The maximum efficiency or also called power coefficient is given by,

\[ C_p = \frac{P_T}{P_{\text{wind}}} \]  

(6)

where \( P_{\text{wind}} \) is the total wind power from equation (4), \( P_T \) is the turbine power which in ideal condition
is \( P_T = P_{\text{wind}}. \) According to the Betz Limit, the maximum value of efficiency or \( C_p \) a wind turbine can
achieve is 59.3% or 0.593 [21]. Since the turbine power is obtain from the electrical output of motor the
\( P_T = \epsilon I \) where \( \epsilon \) and \( I \) are the voltage and current output.

2.3. Torque

Torque or circumferential force depends on the wind turbine rated power and rotor rotational speed to
cause a rotation to the wind turbine on its axis. Thus,

\[ T = \frac{P_T\omega}{2} \]  

(7)
where $T$ is the torque in N.m and $\omega = \frac{V}{R}$ is the rotational speed of the blade tip in rad/s, $V$ is the velocity of the blade tip in m/s and $R$ is the rotor blade radius in m.

### 2.4. Tip speed ratio

The relationship between the wind speed and the rate of rotation of the rotor is characterized by a non-dimensional factor known as the Tip Speed Ratio (TSR) or Lambda ($\lambda$). Mathematically,

$$\lambda = \frac{R \omega}{V} = \frac{\text{Tip speed of blade}}{\text{wind speed}}$$  \hspace{1cm} (8)

### 3. Methods and materials

#### 3.1. Experiment parameter

The number of rotor blade and wind speed are the parameters used for this experiment. These parameters are used to determine the effect on the wind turbine performance as shown in table 1, each number of blades will be tested with the respective wind speed. Table 2 shows the blade parameter of the wind turbine, while figure 1 and figure 2 show the wind blade angle and prototype dimension.

**Table 1. Experiment parameter.**

| Number of Rotor Blade | Wind speed (m/s) |
|-----------------------|------------------|
| 2, 3, 4, 5, 6         | 4.70             |
| 2, 3, 4, 5, 6         | 4.90             |
| 2, 3, 4, 5, 6         | 6.10             |
| 2, 3, 4, 5, 6         | 8.30             |

**Table 2. Blade parameter.**

| Parameter               | Value          |
|-------------------------|----------------|
| Height (m)              | 0.06           |
| Radius (m)              | 0.015          |
| Blade radius curve (m)  | 0.011          |
| Blade shaft length (m)  | 0.012          |
| Blade shaft height (m)  | 0.008          |
| Blade Number            | 2,3,4,5,6      |
3.2. Experiment setup

The schematic diagram of the experiment is shown as in figure 3. The distance of the central axis of wind turbine from the wind flow is fixed to 16 cm and by using a thermocouple thermometer the room temperature was measured which is 25°C. The experiment was carried out in an open room space to acquire a close condition to the real environment. The circuit diagram of the setup is shown as in figure 4. A digital Anemometer was placed in front of the wind flow in order to measure the wind speed coming from the hair dryer/fan. Its accuracy can be up to ±(2.0%+50). Notice that, there is digital Tachometer laser pointed at the wind turbine blade. The purpose is to take the reading of the rotational speed of the tip blade which later will be used to calculate the TSR and turbine torque. The accuracy of the equipment is ±(0.05%+1digit). A PicoScope software was used with a hardware device to create an oscilloscope.
and spectrum analyser on the PC. The probes were attached to the positive wire of the DC motor and the circuit ground was at the motor’s screws near the wind turbine. PicoScope can measured data up to 200MSPS sampling rate. When the Light Emitting Diode light up, it indicates the right rotation of the wind turbine during the process. The Savonius type rotor can harvest energy from any direction. Unfortunately, to produce power output, this wind turbine prototype only rotates in single direction which in this case it was clockwise direction. The PicoScope hardware device is connected to the Laptop for a visual display. For the turbine blades, they are coming from a Do-It-Yourself micro wind turbine kit. The original kit only prepared a rotor for 2 and 4 blades of wind turbine. To overcome the problem, a 3 Dimension printing was used to fabricate rotors for 3, 5 and 6 blades. The experimental set up is shown in figure 5.

![Schematic diagram](image1.png)

**Figure 3.** Schematic diagram.

![Experimental circuit diagram](image2.png)

**Figure 4.** Experimental circuit diagram.

![Experimental setup](image3.png)

**Figure 5.** Experimental setup.
The experimental flow chart is shown as in the figure 6. Before starting the experiment, the number of blade rotors and wind speed need to be decided and the PicoScope software is in ready-to-go condition. The voltage and current parameter were set before running the software. The scale was set to the preferred range, so that a proper view of those spectrum can be captured. Next, the software was run for 5 seconds and if there is an overshoot output, adjustment is needed to reset the scale, then re-run the software. If everything is nice, then the data will be recorded in text form into Ms Excel. Repetition of the process is applied to different number of blades and wind speed. The experiment was repeated for five times and the average mean with the lowest standard deviation was chosen for the analysis.

![Experimental flow chart](image)

Figure 6. Experimental flow chart.

4. Results and discussion

The effect of the 2, 3, 4, 5 and 6 wind blades will be discussed and a comparison will be made between them to see which one is better in performance than the others.

Figure 7 and figure 8 shows the effect of the voltage and current output on the number of blades at different wind speeds. In general, as the wind speed increased from 4.7 m/s to 8.1 m/s, the voltage and current also increased. This is due to the increased of per same swept area of the wind turbine. It can be seen, that the starting point of continuous rising voltage and current between the blades is different. For 2, 3 and 4 blades rotor, the stable rising voltage and current started when the wind speed was around 6.1 m/s. Means that the low wind speed is not enough to generate high electricity for these number of blades. While for 5 and 6 blades rotor started when the wind speed was below 4.9 m/s. Unfortunately, above wind speed 6.1 m/s the voltage started to fall with current slowly increased. At this point, 5 and 6 blades rotor are no longer able to work properly due to its limitation of noises and vibration effect. Moreover, it has passed its optimum voltage around wind speed 6.5 m/s.
Figure 7. Effect of Voltage output on the number of blades at different wind speeds.

Figure 8. Effect of Current Output on the number of blades at different wind speeds.

Figure 9 shows the effect of mechanical power on the number of blades at different wind speeds. The mechanical power increased as the number of blades increased which corresponds with findings reported by Mahmoud et al. [22]. The 3 blades rotor gives highest mechanical power at wind speed 8.3 m/s. The power increased to around 370 mW. It shows that the 3 blades rotor is more efficient than 2, 4, 5 and 6 blades rotor at higher wind speed. On the other hand, the power for 5 and 6 blades rotor, increased significantly starting at wind speed of below 4.9 m/s but then slowly increased when above wind speed 6.1 m/s. This due to limitation that the wind turbine is not able to produce more mechanical power at higher level wind speed.
Figure 9. Effect of Mechanical Power on the number of blades at different wind speeds.

Figure 10 shows the effect of theoretical power on the number of blades at different wind speeds. Notice the scale on the graph, if it is compared with the mechanical power, there is huge gap between the actual and ideal power output. Several factors might have affected the actual performance. These factors could be due to mechanical losses during the process, external factors, geometrically or due to human error.

Figure 11 shows the effect of power coefficient on the number of blades at different wind speeds. It appears that the power coefficient for 5 blades followed by 6 blades has a noticeable increasing value than the 3 and 4 blades rotor from wind speed 4.7m/s to 6.1 m/s. This may be due to the net drag force affected on rotor is higher than the other at wind speed 6.1 m/s [22, 23]. Unfortunately, the value started to decrease slowly above wind speed 6.1 m/s. While for 3 and 4 blades, the $C_p$ decreased at early wind speed between 4.7 m/s to 6.1 m/s and then increased steadily above wind speed 6.1 m/s. It can be seen that the highest power coefficient is around 0.13 (13%) which achieved by 3 blade rotors. The drag force for this blade rotors is higher when the wind speed is increased. The 2 blade rotors started with high power coefficient compared to the others at 0.08 (8%) which means the low wind speed is suitable for this blade number. But above wind speed 4.9 m/s the efficiency started to fall which was below the value for 5 and 6 blades. Then increased back when reached wind speed 6.1 m/s. The drag force is high at high wind speed. The cause of this irregularity might be because of vibration occurs which limits the rotation or the experimental test rig is not set up properly.
Figure 11. Effect of Power Coefficient on the number of blades at different wind speeds.

Figure 12 and figure 13 show the effect of tip blade rotational speed and torque on the number of blades at different wind speeds. It shows that the higher the rotor blade numbers the higher the rotational speed of the tip blade, but lower torque value was produced. Vice versa, when the number of blades is lowered, the tip blade rotational speed is lowered but bigger torque value was produced. As the rotational speed of the tip blade increased, so does the noise level. The rotational speed was reduced at certain wind speed in order to counter the noise level, which in this study, it started from wind speed around 6.1 m/s and above. As analysed by R. Haryanto et al [24] the torque value is directly proportional to the wind speed and the effect can be seen on figure 13. Based on the figure 13, 2 blades rotor has higher torque of 0.15 mN.m at wind speed 4.7 m/s while 3 blades rotor has significant value of 0.5 mN.m at wind speed 8.30 m/s. According to M. H. Ali (2013), increasing the blade number will increased the drag surfaces against the wind flow and reduced the net-working torque on the blades [26].

Figure 12. Effect of Tip Blade Rotational speed on the number of blades at different wind speeds.
Figure 13. Effect of Torque on the number of blades at different wind speeds.

Figure 14 shows the effect of tip speed ratio of the blade rotor on the number of blades at different wind speed. The 6 blades rotor wind turbine has the highest tip speed ratio than the other with value around 13 at wind speed 6.1 m/s. In general, the optimal tip speed ratio decreases with higher wind speed. The wind turbine has the optimal tip speed ratio at the highest peak which is above wind speed 6.1 m/s. Tip speed ratio is related with the rotational speed of the tip blade rotor. F. Wenehenubun et al. [26] analysed that when the rotational speed is higher, the tip speed ratio is higher. However, the highest performance only can be achieved at relatively low tip speed ratio because the rotational speed must be lowered to reduce the noises and vibrations. But also, not too low, otherwise the wind turbine cannot harness enough wind energy.

Figure 14. Effect of Tip Speed Ratio on the number of blades at different wind speeds.

Above all the results and discussions, the performance of the blade rotor number is best achieved by 5 blade rotors. The decision is made based on reference to Malaysia’s average wind speed. Malaysia’s average wind speed is approximately around 2.00 m/s to 5.00 m/s overall. (source: https://www.windfinder.com). However, in some region with mighty buildings, tall trees and sea shore, the wind flow can be transformed into wind gust where the wind speed might reach up to 7.0 m/s or even more in Malaysia. (source: WorldWeatherOnline.com). It can be seen in figure 9 that 3 blade rotors give highest mechanical power above wind speed 6.1 m/s. Even though it is still in range with Malaysia’s average wind speed but it is not suitable because the power only increases at higher wind speed and remain steady at lower wind speed. In contrast with 5 blades, the output started to increase before 4.9 m/s...
until 8.3 m/s. The wind turbine which can give out power faster at low wind speed is more desirable because to wait for the wind to be at higher level is unpredictable.

Figure 15 shows the effect of power coefficient against tip speed ratio of 5 blade rotors. The first point to notice is the maximum value of the $C_p$ is only 0.109 (10.9%) at a TSR of 8.28, which is below the Betz limit [27]. The difference might be caused by the drag and tip losses which reduced the rotor efficiency. However, at this point, M. Ragheb (2014) stated that the mechanical power is at maximum extraction and the tip speed ratio is at optimum [28].

**Figure 15.** Effect of power coefficient against tip speed ratio of 5 blade rotors.

Figure 16 shows the effect of torque against TSR of 5 blade rotors. It can be deduced that the higher the tip speed ratio the higher the torque produced. Unfortunately, at certain point, the torque will be decreased because of the rotational speed of the blade rotors is too high, which make the wind turbine unable to extract more power due to the vibration effect.

**Figure 16.** Effect of torque against tip speed ratio of 5 blade rotors.

Figure 17 shows the effect of mechanical power against tip blade rotational speed of 5 blades rotor. Since the TSR is directly proportional to the rotational speed so the power and torque result will be affected as well. The higher the rotational speed the higher the mechanical power. But at certain point, the power value will be decreased due to high rotational speed and limitation to the geometry.

**Figure 17.** Effect of mechanical power against tip blade rotational speed of 5 blades rotor.
5. Conclusions
An experiment of determining the effect of number blade rotors at different wind speed to the performance of the wind turbine had been studied. Overall in these studies, it can be concluded that 5 blades rotor shows the highest performance compared to the 2, 3, 4 and 6 blades rotor with Malaysia’s average wind speed as the guideline. The power produced is increased as the wind speed is increased. At wind speed 6.1 m/s, 5 blades rotor produced optimum mechanical power of 260 mW, power coefficient of 0.109 (10.9%), torque at 0.12 mN.m and relatively low tip speed ratio of 8.28. This number of blades will be a suitable wind turbine for further development.

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