Study of Pivot Panel Mechanism on the Self Start-Ability of a Darrieus Wind Turbine

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Abstract. In South East Asia countries such as Malaysia, wind turbine is generally not suitable to be used in large scale to generate electricity due to inconsistent wind speed and suitable land site availability. However, a small scale application is of preference as the wind speed in the region lies within the low speed range of approximately 2-5 ms⁻¹ with intermittent highs up to 8 ms⁻¹. The performance of Vertical Axis Wind Turbines (VAWTs) is known to be better compared to Horizontal Axis Wind Turbines (HAWTs) in urban conditions due to its omnidirectionality, which allows it to operate in fluctuating turbulent wind conditions. However, the major drawback of VAWTs is the inability to self-start under low wind speed conditions. Hence, the objective of this work is to investigate the Pivoting Panel Mechanism (PPM) which aims to assist VAWT models to self-start at low wind speed condition. Three sets of PPM width configurations (70mm, 80mm, 90mm) are used to study the effect of increasing the pivot panel surface area on the VAWT performance. Performance test showed that the PPM model improved the power coefficient values at the tip wind speed range of TSR<0.75 (PPM 70mm>80mm>90mm). Further investigation revealed that the larger PPM surface area (90mm) was able to assist the VAWT model to achieve a shorter RPM response time at wind speed of v = 2.5ms⁻¹ and 2.9ms⁻¹. These findings have considerable implications for future researches for the optimization of PPM design parameters and its adaptations in VAWT turbine design.

Keywords: hawt, low wind speed, wind turbine

1. Introduction

The global power sector is witnessing a gradual transition from conventional thermal power-generating sources toward renewable energy technologies. The establishment of supportive policies and regulatory frameworks in various countries, particularly by China and India, has facilitated the growth of renewable energy in the past decade. Therefore, the falling cost of solar and wind electricity has led to a boom in the construction of utility-scaled power projects (Global Data Energy, 2018). Consequently, global investments in renewables from 2001-2018 consistently exceeded USD$200 billion (McCrone and Mosiener, 2018).

One of the potential renewable energy sources for Malaysia is wind energy. There are many sites in Malaysia that are geographically strategic for large scale electricity power generation, which are Kudat, Kota Bharu, Sandakan, Miri and Kota Kinabalu. Albani, et al (2013) conducted a simulation analysis using a 22kW rated power wind turbine using the WindPro software to estimate the wind potentiality in Malaysia based on the METAR data available from 2005-2011. Simulation results yielded that Kudat is predicted to generate the highest annual energy production at 14.6
MWh/year as well as highest capacity factor and full load hour at 7.6% and 661 hours/year respectively, which is made possible by the highest wind power density of 21 W/m² produced and Weibull scale parameter for wind speed of 2.8 ms⁻¹. On another perspective, it has been revealed in a study that the rate of urbanization in a country has a direct negative influence on urban wind speeds and the surrounding areas (Liu, 2018). Statistics revealed that the rate of increase of urbanization rate is linear, from 68.36% in 2007 to 76.01% in 2017 (Greenfield, 2018). Therefore, the average wind speed for Malaysia may be lower than the predicted range of (<2ms⁻¹) in most areas in Malaysia. The commercialization of the wind turbines requires a minimum cut-in speed of 4 ms⁻¹ for electricity power generation (Chinnasamy, 2015). As a result, small-scaled wind energy harvesting is potentially more practical to be applied in Malaysia, particularly in Sabah.

2. Literature review

2.1 Low wind speed wind turbine

Wind turbines are categorized into two major types, which are the Horizontal Axis Wind Turbine (HAWT) and the Vertical Axis Wind Turbine (VAWT). The difference between the HAWT and the VAWT is the orientation of the axis of rotation of the main shaft which is connected to the wind turbine blades. HAWT produces more power output than VAWT, but it requires high wind speeds for it to function operationally and to yield maximum performance. Therefore, HAWT is not a practical choice for the renewable energy industry in Malaysia due to the low average wind speed (<2ms⁻¹). On the other hand, VAWT design models are relatively quieter, produces less stress on the support structure and most importantly omni-directional. In addition, VAWT has the capability to generate power without requiring much wind, enabling the generator and transmission mechanism to be installed close to the ground where wind speed is low. This allows for relatively easier maintenance processes than HAWT, which are installed at the top of the tower at a height potentially reaching up to 126 m. Therefore, the development of VAWT technology in Malaysia is more feasible than HAWT predominantly due to its ability to generate power at low turbulent wind speeds in any wind direction (Kumara, 2017).

There are two major types of VAWT, which are the Savonius rotor and the Darrieus rotor. The Darrieus rotor is a lift-type VAWT, featuring the employment of aerodynamically shaped rotors which facilitates the generation of lift force to rotate the turbine operationally. The use of airfoils as the blades of the rotor multiplies the wind speed passing through it, giving it a large TSR ratio of more than 1. Therefore, the Darrieus rotor is more efficient than the Savonius rotor, but only at high wind speed conditions. The Darrieus rotor has a major drawback of low initial torque generation, and therefore has difficulty to self-start at low wind speed conditions. Therefore, many researchers had attempted to came out with innovative design such as integrating the Savonius rotor into the Darrieus rotor to create a new VAWT hybrid design model to overcome the weakness of the Darrieus rotor or improving the design of the Darrius blade itself (Oskarsdottir, 2014; Chua et al., 2014; Jamamun et al., 2017; Misaran et al., 2017). Passive and active pitch mechanism are also incorporated into the Darrieus design model to enhance the self-starting capability and to optimize the efficiency.

Abid, et al (2015) designed, constructed and tested a 3-bladed Darrieus turbine with an external Savonius turbine mounted on top of it. Experimental results showed that the slight Savonius modification enabled the turbine design to self-start more easily at low wind speed conditions. Sharma, et al (2013) attempted to measure the performance of the designed 3-bladed Darrieus-Savonius turbine using the pitot-tube wind tunnel set-up with 5 various overlap ratios ranging from 10.8-25.8%. The experimental results revealed that the Cp increases as the overlap ratio increases until it reaches an optimum point of 0.53 at 0.604 TSR and 16.8% overlap, concluding that the hybrid design is capable of self-starting. Another hybrid Darrieus-Savonius turbine design is proposed, which latter component is attached at the centre of the shaft. The hybrid design combines the relatively higher efficiency features of the former and the self-starting capabilities of the latter. The performance parameter chosen in the research is the coefficient of power, Cp. The experimental analysis was conducted using a wind tunnel set-up, which results showed that the hybrid turbine yielded a relatively higher Cp value (0.23) in comparison with the Darrieus turbine (0.21) and the Savonius turbine (0.19) at low wind speed conditions (2-4 ms⁻¹). However, the of the Cp of the hybrid turbine showed a significant decrease at high wind speed condition (>4 ms⁻¹), which may be attributed to the
overall heavier structure and predominantly the large drag force exerted on the Savonius component (Kavade and Ghanegaonkar, 2017).

Kiwata, T. et al (2010) developed a unique VAWT model equipped with a double crank link mechanism constituting the variable pitch blade angle mechanism, imbuing the design with smooth wind directionality. The performance parameter is dependent on the blade pitch angle amplitude, the number of blades and the airfoil profile. The constructed prototype is tested experimentally in a wind tunnel set-up. Results showed that the self-start capabilities of the design is same as the fixed pitch blade mechanism, but yielded a significant increase of rotational speed, achieving a maximum $C_p$ of 0.22 at 1.2 TSR. Portillo et al (2016) designed, simulated and constructed a VAWT model with an active pitch mechanism, which is guided by a wind vane mounted on top of the main shaft. The Double Streamtube Model is utilized to predict the performance of the turbine using MATLAB and ANSYS software. The experimental results showed that the turbine was able to self-start at low wind speed range (3.6 ms$^{-1}$) and capable of generating electric power of 120W at high wind speed conditions (up to 7.6 ms$^{-1}$) with an efficiency of 35%. Another research proposed a design model consisting of the combination of a conventional five straight-bladed Darrieus VAWT with flat-plated flap mechanism. The resultant hybrid VAWT design successfully self-started under low wind speed conditions at 1ms$^{-1}$ and recorded an average increment of 2-5% power output compared to the conventional Darrieus VAWT. However, the hybrid design with the fixed flap mechanism recorded a drop in performance at higher wind speed conditions (>3 ms$^{-1}$) (Hasnuddin, 2018).

According to World Weather Climate and Information (2019), it is shown that the average wind speed in Sabah is approximately 2.0 ms$^{-1}$. Therefore, it is a necessity for designed VAWTs to achieve self-start capability in the low wind speed range of 2-5 ms$^{-1}$.

2.2 Model description

2.2.1 Design of Pivot Panel Mechanism (PPM)

The pivoting panel concept is adopted by Yoon (2013), who designed the panels in such a way that the panels are oriented 90° with respect to the supporting arm in the leeward direction and flaps up in the windward region. Therefore, a net torque is produced due to this configuration, providing additional drag forces which can potentially boost the power output and increase the self-starting capacity of VAWT design models. The counterweight mechanism concept is adopted from Borkar (2018), who designed a tilted flap mechanism that passively adjust the pitch due to the motion of wind itself whereby the flap is close up in leeward region by the action of gravity and open up in the windward region utilizing the action of wind. Thus, a hybrid wind turbine as shown in figure 1 is designed and assessed.

![Figure 1: VAWT with pivot panel](image)
2.2.2 Experimental setup

Four different configurations of the Darrieus VAWT model as shown in table 1 were tested; in order to determine the effect of increasing the plate surface area (aspect ratio) in contact to the wind on the response time and power coefficient; within the wind speed of up to 5 ms$^{-1}$.

| Table 1: Pivot panel configuration |
|------------------------------------|
| Material: Aluminium Alloy 1060     |
| Configurations | Length, L (mm) | Width, B (mm) | Aspect Ratio (L/B) | Thickness (mm) |
| Pivot Panel 1 | 150            | 70            | 2.14              | 0.4            |
| Pivot Panel 2 | 150            | 80            | 1.89              | 0.4            |
| Pivot Panel 3 | 150            | 90            | 1.67              | 0.4            |

Six air blowers are arranged in a 2x3 configuration as shown in Figure 2. The air blowers used have a diameter of 30 cm, with a rated air flow rate of 62 m$^3$/min and a rotational speed of 2900 rpm. The distance between the Darrieus VAWT model and the air blowers are varied to obtain different wind speeds that is acting on the model, which are assigned from 1m to 13 m in steps of 2 m. The average wind speed for the 7 sets of distances are measured using the digital hand-held anemometer while the turbine rotation speed were measured using wireless magnetic speedometer attached at the wind turbine shaft. The obtain wind speed and wind turbine rotation speed are used to calculate the tip speed ratio (TSR).

3. Results and discussion

3.1 Effect of PPM on wind power performance

The PPM (70mm, 80mm, 90mm) configurations are compared as shown in Figure 3. It is noted that at the wind speed of (V=3.8ms$^{-1}$, 4.1s$^{-1}$, 4.7ms$^{-1}$), the power coefficient and power output of the PPM 90mm model is slightly higher than the 70mm and 80mm counterparts. The possible explanation to this experimental outcome may be due to the better ability of the pivot panel of width 90mm to flap up and down of the in the upwind windward and upwind leeward region respectively at higher stable RPM. The former flap up motion in the upwind windward region accounts for the unconstraint motion about the hinge pin, which may exert minimal opposite torque. On the other hand, the latter flap down motion in the upwind leeward region allows the incoming wind to exert positive torque. Since the PPM 90mm has a larger surface area in contact to the wind, therefore more positive torque is
generated compared to the 80mm and 70mm PPM configuration (PPM 90mm > PPM 80mm > PPM 70mm) since the wind force impacting the pivot panels are sufficiently high for the PPM 90mm to flap.

However, it can be observed at the wind speed range of (V=2.2 ms\(^{-1}\), 2.5 s\(^{-1}\), 2.9 ms\(^{-1}\), 3.2 ms\(^{-1}\)), the PPM 70mm yielded approximately similar power coefficient with PPM 80 mm, but slightly higher than PPM 90 mm. The possible reason of this occurrence may be due to the decreasing ability of the pivot panels PPM 80 mm and 90 mm to flap up at V<3.2 ms\(^{-1}\) (corresponds to lower stable operating RPM). Therefore, the induced opposite drag force especially for PPM 90 mm may be higher at stable operating RPM conditions compared to PPM 70 mm and 80 mm. Hence, this also suggest that the weight factor (Tong, 2010) and the ability of the pivot panel to flap collectively influences the power coefficient and the power output of the PPM VAWT model.

Figure 3 : Graph of Power Coefficient vs Wind Speed (PPM only)

The PPM models yielded a marginally higher power coefficient at approximately the range of TSR<0.75 compared to a standard VAWT. For instance, the PPM 70 mm, 80 mm and 90 mm yielded a power coefficient improvement up to approximately 37%, 26%, 17% respectively compared to the standalone VAWT model at TSR=0.5. Therefore, this suggest that the PPM model may enhance the self-start capacity of the VAWT model at TSR<0.75, since it is observed in the experiment that the standard VAWT experience considerable delay to self-start at a wind speed range of V<3.2ms\(^{-1}\).

Figure 4 : Power Coefficient vs Tip Wind Speed Ratio (0.2<TSR<1.3)
3.2 Wind turbine response time at low wind speed

The wind turbine response time analysis shows how the turbine reacts to average wind velocity as shown in figure 5. The PPM model in figure 5(a) showed a slightly sharper rise of RPM compared to the standalone model (9.7 RPM) for PPM 80 mm (11.8 RPM, +21%) and PPM 90 mm (11.1 RPM, +14%) at the wind speed of $v=2.9$ ms$^{-1}$ at the initial 20 seconds (starting phase). This experimental data may be consistent with the experimental observations whereby the pivot panels in PPM 70 mm experience difficulties in flapping while the PPM 80 mm and 90 mm can flap relatively well at the starting phase. This suggests that the PPM has the potential to assist the VAWT model to self-start to a higher speed at a shorter amount of time compared to the standalone model, provided that the pivot panel in the upwind windward direction can flap up in the starting phase to cancel out the generation of opposite torque.

This phenomenon is further observed at 2.5 ms$^{-1}$ as shown in Figure 5 (b); PPM 90 mm showed a slightly sharper RPM rise (8.8 RPM, +28%) compared to the standalone model (6.9 RPM) within the initial 20 seconds (starting-phase) while the PPM 80 mm and 90 mm configurations does not. This occurrence is quite consistent with the experimental observations whereby the pivot panels of the PPM 90 mm can flap well at the starting phase whereas the other plates in the other configurations pivoted relatively poorly. This may be attributed to the relatively larger surface area in contact to the wind for the 90 mm width plate compared to the 70 mm and 80 mm counterparts, corresponding to more wind force acting on the plate.

However, it is observed that for the wind speed of $v=2.2$ ms$^{-1}$ as shown in Figure 5 (c), the sharp rise of RPM in the initial 20 seconds is not observed like the previous two cases discussed above. This occurrence is also consistent with the experimental observations whereby the pivot panels of the PPM (70 mm, 80 mm, 90 mm) demonstrate poor flapping ability at the starting phase, which in fact contributed to the occasional stalling of the PPM VAWT model as the experiment is repeated due to the opposite torque generated. The possible reason for this occurrence may be due to the
insufficient wind force exerted on the 90mm pivot panel for it to flap up in the upwind leeward direction.

4. Conclusion
As a conclusion, this study have shown that both the PPM 80 mm and 90 mm VAWT models are able to assist the VAWT model to self-start at the wind speed of $v=2.9\text{ms}^{-1}$. On the other hand, only the PPM 90 mm model is observed to improve the self-starting capability of the VAWT model at the wind speed of $v=2.5\text{ms}^{-1}$ within the initial 20 seconds (starting phase). At the lowest wind speed of $2.2\text{ms}^{-1}$, all the PPM VAWT models are observed to lack the ability in assisting the VAWT model to self-start. Power coefficient analysis of the turbine showed a relatively higher power coefficient at TSR<0.75. It is calculated that the PPM 70 mm ($C_p=8.0\times10^{-3}$), 80 mm ($C_p=7.3\times10^{-3}$) and 90 mm ($C_p=6.8\times10^{-3}$) yielded a power coefficient improvement up to approximately (37%, 26%, 17%) respectively compared to the standard VAWT model ($C_p=5.8\times10^{-3}$) at TSR=0.5.

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