Performance of Stacking a Darrieus-Savonius Wind Turbine for Low-Speed Operation

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ABSTRACT

Wind power is a form of green energy that makes no pollution when used as an operational system. The low-speed wind turbine is very interesting for harvesting energy with a wide range of applications. Derrieus and Savonius are vertical wind turbines that can be operated with low complications. Lighter materials used for producing the blades can reduce the gravitational force, leading to faster start-up of the wind turbine operation. Savonius (Interference of shaft type) was located at the upper and Darrieus (H-type) was located at the lower (Model B2) in a vertical turbine fabricated by acrylic plate, which could start-up at a low speed of 1.52 m/s. Therefore, the novel stacking of Darrieus–Savonius turbine and lightweight acrylic materials could promote the vertical axis wind turbine for low-speed operation.

KEYWORDS: Savonius, Darrieus, Vertical Axis Wind Turbine, Low Wind Speeds

บทคัดย่อ

พลังงานลมเป็นพลังงานที่อยู่ในรูปของพลังงานสะอาดซึ่งไม่ก่อให้เกิดมลพิษเมื่อใช้เป็นแหล่งกำเนิดพลังงาน กังหันลมความเร็วลมต่ำเป็นเทคโนโลยีที่น่าสนใจอย่างมากสำหรับการนำมาเพื่อใช้ในการเก็บเกี่ยวพลังงาน เนื่องจากสามารถใช้งานในย่านที่กว้างขึ้น กังหันลมแบบ แดร์เรียส และ ซาโวเนียส เป็นกังหันลมแนวแกนตั้งที่สามารถทำงานได้ที่ความเร็วลมต่ำ การนำเอาวัสดุที่มีน้ำหนักเบามาใช้ในการสร้างใบกังหันลมสามารถลดแรงกระทำจากแรงโน้มถ่วง ที่เกิดขึ้นกับตัวกังหันลม ซึ่งมีผลทำให้การออกตัวของใบกังหันลมง่ายขึ้น กังหันลมแบบซาโวเนียส (ลักษณะการโค้งรอบเพลา) ติดตั้งไว้ด้านบนและติดตั้งกังหันลมแบบแดร์เรียส (ลักษณะทางกายภาพแบบตัวอักษรเฮช) ไว้ตำแหน่งด้านล่าง (โมเดล B2) ใช้อะคริลิคเป็นวัสดุในการผลิตใบกังหันลม ซึ่งการทำงานของระบบกังหันสามารถเริ่มต้นที่ความเร็วลม 1.52 เมตรต่อวินาที ด้วยเหตุนี้ การนำกังหันลมแบบแดร์เรียส-ซาโวเนียส มาเรียงซ้อนกันแบบ 2 ชั้นแบบใหม่ และรวมถึงการใช้วัสดุอะคริลิคที่มีน้ำหนักเบาสามารถช่วยให้กังหันลมแนวแกนตั้งทำงานได้ที่ความเร็วลมต่ำ

คำสำคัญ: ซาโวเนียส แดร์เรียส กังหันลมแนวแกนตั้ง ความเร็วลมต่ำ

Introduction

Fossil fuel pollution and related energy resource depletion creates interesting challenges to decrease emissions through the application of alternative energies (Tahani, Rabbani, Kasaeian, Mehrpooya, & Mirhosseini, 2017). Energy has been essential for the continuous advancements and economic expansion seen in recent decades. Providing suitable and low-cost energy sources is essential to reduce poverty, develop human satisfaction, and improve living standards worldwide (Ramadan, Yousef, Said, & Mohamed, 2018). Alternative renewable energy resources have been reported to emit low pollution and be friendlier to the environment, such as solar, wind, biomass, tidal, ocean waves and so on.

Wind energy is one of the most interesting alternative energy technologies. It is well known as being pollution-free, excessively available in the atmospheric earth, and locally transformed. It can support decreased dependency on fossil fuels such as gas and oil. Many developing countries have already realised the high potential of wind power as a resource for energy generation since it is effective for the utilisation of power production (Mohamed, Janiga, Pap, & Thévenin, 2010).

Wind energy transforms free kinetic energy in the wind into electricity, through pollution-free process. Wind turbine technologies are categorised into various sizes dependent on their energy generating capacity. There are also different types with distinct rotor designs.

Small wind turbines are defined as those that have a capacity rating of less than 10 kW, which is significantly lower than utility-scale turbines which have capacity ratings ranging from 100 kW-5 MW. Small-scale wind turbines have excellent characteristics such as low price, relatively short pay-back periods, and high performance and reliability. They are comfortable for use in a number of locations including offshore platforms, sailboats, telecommunications transmitters and remote military posts (Liang, Fu, Ou, Wu, Chao, & Pi, 2017).

Generally, wind turbine technologies can be divided into vertical-axis wind turbines (VAWTs) and horizontal-axis wind turbines (HAWTs). However, they both perform with the same ideal efficiency. The majority products available on the trade are often the HAWT type.

The producing level of VAWTs (Savonius-Darrieus) is obviously low mature than those for HAWT. On the other hand, the disadvantages of HAWT are represented such as high-cost, noise, high wind speed for cut-in. Previous reports (Gsänger & Pitteloud, 2014) for HAWTs, the development of 18% produced in VAWTs (Savonius-Darrieus) that has numerous advantages including easy maintenance, omni-directionality, and reduced noise. Therefore, VAWTs (Savonius-Darrieus) have more development and research provided in terms of wind turbine platforms for novel small-scale energy generation, when compared by HAWT system.

Based on the VAWTs rotor, VAWTs rotors comprise different types such as Savonius, helical Savonius, Eggbeater Darrieus, H-Darrieus, combined configuration of Savonius and Darrieus rotor.

Purpose

In this investigation, focusing on the vertical axis wind turbine is conducted in low-speed wind. Darrieus-Savonius rotors are combined with the performance of 3-blades for initial start-up at low-speed wind. Study of the properties was operated when combined between Darrieus and Savonius at different positions, which are switched between the upper and lower, as shown in Figure 1-2. Comparison of the weight of materials was carried out for all fabricated blades and measured properties of the wind turbine to be the best low-speed VAWTs.

Benefit of Research

The stacking Savonius and Darrieus started developing vertical axis wind turbines that can start at low speeds of around 2 m/s. This low speed operation broadened the applications suitable Thailand's location. Meanwhile, the lighter blade weights reduce the force of gravity force allowing it to start running at low wind speeds and generate high performance.

Research Process

This investigation provided the design of the blades of a vertical wind turbine that focused on the Savonius and Darrieus rotors for cut-in at low wind speeds of around 2 m/s. Savonius (Interference of shaft type) (Akwa, Vielmo, & Petry, 2012) and Darrieus (H-typ) (Hashem & Mohamed, 2018) were used to exam the properties of the blade. In order to study the properties, they were classified into 2 models, as shown in Table 1. Savonius (Interference of shaft type) was produced from stainless sheet steel. Darrieus (H-type) was produced from natural rubber combined with glass fiber and resin, called Model A. Based on the investigations, both of these blades were switched for location between upper and lower, as shown in Figure 1. Savonius was located at the lower and Darrieus was located at the upper, called Model A1. Savonius was located at the upper and Darrieus was located at the lower, called Model A2, while Savonius (Interference of shaft type) and Darrieus (H-type) were produced from acrylic, called Model B. When operating the system, both of these blades were switched for location between the upper and lower, as shown in Figure 2. Savonius was located at the lower and Darrieus was located at the upper, called Model B1. Savonius was located at the upper and Darrieus was located at the lower, called Model B2.

Instruments

The wind tunnel experiments were conducted with an open test using the facilities at the Department of Electrical Engineering, Prince of Songkla University, where the wind tunnel structure is made from iron sheets. The wind tunnel is driven by an inverted speed AC motor. The test section had a length of 2.4 m and offered a 1.2 m × 1.2 m cross-section. The inlet of the wind tunnel had a honeycomb structure installed in order to reduce turbulence and make the wind more streamlined before reaching the wind turbine. The maximum wind velocity generated reached 4 m/s, but these experiments were carried out in the low range of wind speeds at 1.5-4.0 m/s. This investigation measured the flow field around the wind turbine by anemometer brand UNI-T model UT363 with a range between 0-30 m/s (±5% rdg+0.5). The Digiton Photo Tachometer model DT-2234C+ with an accuracy of ±0.1 RPM was used to record the rotational speed. In the section torque of the rotor was used torque transducer, unhurried loads were applied to the turbine shaft through an axis connected to the torque transducer; model WSC3-030CN with the range and accuracy at 6-30 Nm, ± 3% (CW), experimental apparatus as shown in Figure 3.

Table 1 Geometrical details for the Savonius and Darrieus wind turbines

Geometrical structure	Values			
	Model A		Model B	
	Savonius	**Darrieus H-type**	**Savonius**	**Darrieus H-type**
Number of blades	3	3	3	3
Blade height (H)	0.45 m.	0.60 m.	0.45 m.	0.60 m.
Blade dimension (D)	0.80 m.	0.72 m.	0.72 m.	0.72 m.
Blade thickness (t)	1×10^{-3} m.	2×10^{-3} m.	2×10^{-3} m.	2×10^{-3} m.
Materials	Stainless sheet steel	Natural Rubber + Fiberglass	Acrylic	Acrylic
Weight	17.70 kg.	8.90 kg.		

Figure 1 Vertical axis wind turbine, denoted as Model A. Darrieus (H-type) was fabricated by stainless sheet steel, while Savonius (Interference of shaft type) was fabricated using stainless sheet steel (A1). Darrieus (H-type) was located at the upper, while Savonius (Interference of shaft type) was located at the lower. (A2) Savonius (Interference of shaft type) was located at the upper, while Darrieus (H-type) was located at the lower

Figure 2 Vertical axis wind turbine, denoted as Model B. Darrieus (H-type) and Savonius (Interference of shaft type) were fabricated by acrylic (B1) Darrieus (H-type) located at the upper. Savonius (Interference of shaft type) was located at the lower. (B2) Savonius (Interference of shaft type) was located at the upper, while Darrieus (H-type) was located at The lower

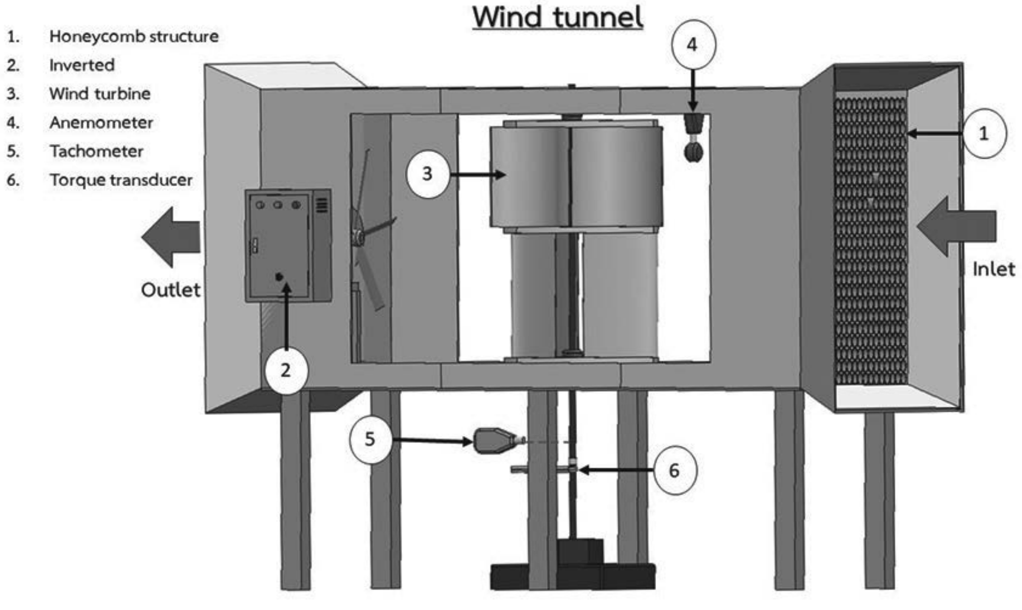

Figure 3 Schematic diagram of experimental apparatus

Source: Elkhoury, Kiwata, & Aoun (2015)

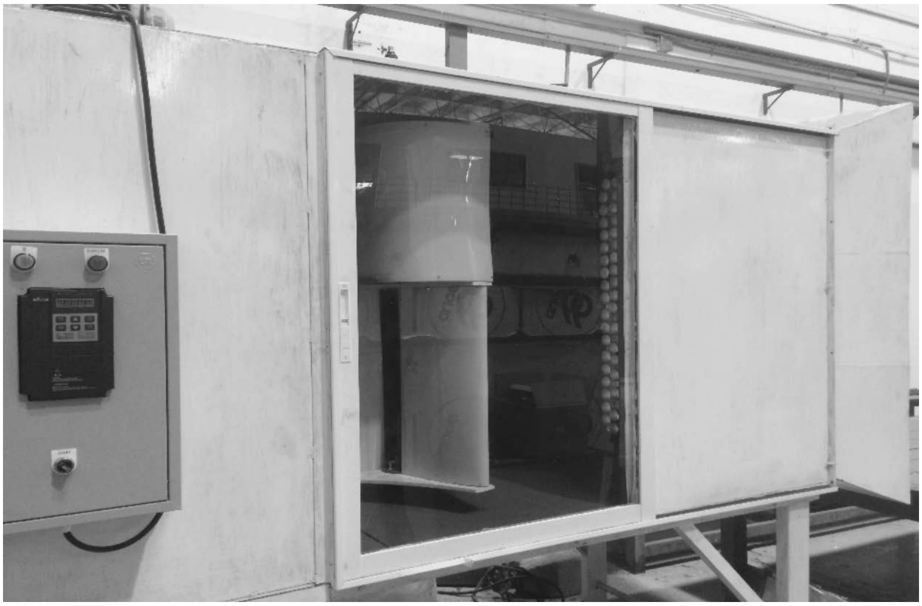

Figure 4 An experimental wind tunnel measuring a vertical wind turbine

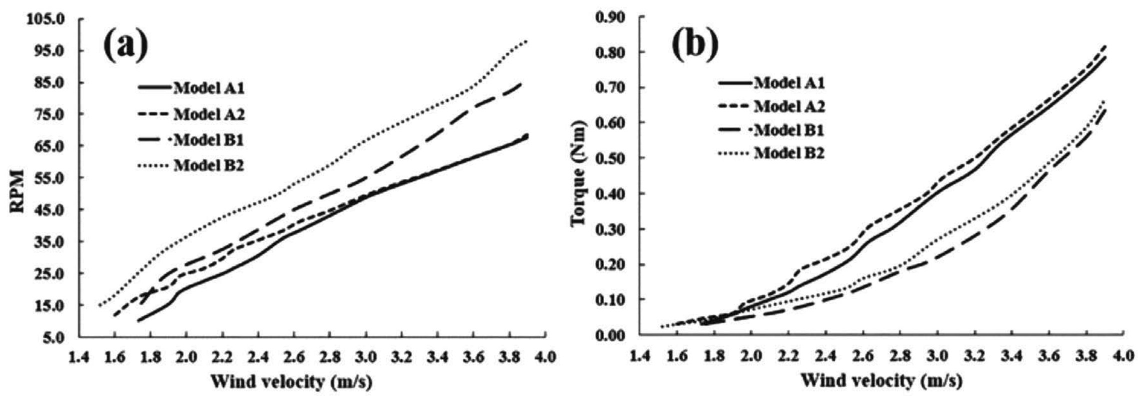

Figure 5 Vertical wind turbine behaviour showing (a) the relationship between wind velocity and rotational speed and (b) the relationship between wind velocity and torque

Data Analysis

Figure 4 shows the real experimental wind tunnel measuring vertical wind turbines with blades constructed from acrylic, stainless sheet steel, and natural rubber + fiberglass. Figure 5(a) shows the relationship between wind velocity and rotational speed for comparing the vertical wind turbine of 3 models including Model A1, Model A2, Model B1, and Model B2. Based on the low speed wind turbine, the wind turbine needs to operate at lower than 2 m/s. This result indicated that Model A2 and Model B2 had higher performance than Model A1 and Model B1. The structures of Model A2 and B2 were fabricated by Savonius located at the upper position and Darrieus located at the lower position. Additionally, Figure 5(b) shows the relationship between wind velocity and torque, which indicates that Model A performed better than Model B, leading to Model A being heavier than Model B by approximately 50%. However, the low speed condition of this investigation focused on Model A2 and Model B2 (Savonius was located at upper, Darrieus was located at lower), which had start-up low speed ranges between 1.52-1.60 m/s. The best start-up at a low speed of 1.52 m/s was occupied by Model B2 produced from lightweight materials.

Blade-fluid interaction confirms the expanded clearly concentration of vortices on the downstream of the Darrieus rotor in comparison to the downstream of the Savonius rotor that can produce the Coanda effect. This reaction is associated with the squeezing of the vortices on the downstream of Darrieus rotor due to forcing the rotor into this rotation. Therefore, this situation can produce power (Ghosh, Biswas, Sharma, & Gupta, 2015). A Darrieus turbine requires low-speed wind to produce the minimum rotational speed, while a Savonius turbine located on the top is attributed to turbine self-start at low wind speed (Abid et al. 2015), as shown in Figure 5(a).

The development of wind turbine technologies has been increasing for the purpose of harvesting higher energy. Increased rotor blade weight in turn increases the size. Thus, gravitational loads become create drivers (MacPhee & Beyene, 2019; Mishnaevsky et al., 2017). For this reason, the blade material needs to be lightweight in order to reduce gravitational loads in low speed wind turbines, as conveyed in Figure 5(b).

Generally, the performance of vertical axis wind turbines is represented by the torque coefficient (C_t), power coefficient (C_p), and static torque coefficient (C_{ts}).

$$C_t = \frac{T}{0.5\rho A V^2 R} \quad (1)$$

$$C_P = \frac{P_{Turbine}}{P_{Available}} = \frac{T\omega}{0.5\rho A V^3} \quad (2)$$

$$C_{ts} = \frac{T_s}{0.5\rho A V^2 R} \quad (3)$$

Where V is the free stream velocity, ρ is air density, A is the swept area of the turbine, R is the radius of the turbine, TSR is the tip speed ratio, T represents the dynamic torque, ω is rotational speed, T_s is the static torque, and $P_{Turbine}$ and $P_{Available}$ represent the power resulting from the turbine and available wind power, respectively.

Figure 6(a) shows the relationship between the tip speed ratio (TSR) and coefficient of power (C_p), which indicated that Model B1-B2 series was higher for TSR than Model A1-A2. Model A1-A2 initially showed initially a different trend at a range 0.2-0.5 TSR and then overlapping trends were performed at a range between 0.5-0.6 TSR. On other hand, Model B1-B2 showed initially overlapping trends in a range between 0.3-0.5 TSR and then the trends were clearly split at a range between 0.5-0.9 TSR. Models A and B were revealed at approximately 0.23 C_p. However, Model B2 had the highest performance with 0.27 C_p and 0.9 TSR.

The Reynolds number is one of the factor parameters forcing the rotation of velocity and inflow velocity, at which the turbine occupies its maximum performance coefficient (C_p). The lift produced by the blades is dependent on the Reynolds number, which in turn depends on the wind speed (Elkhoury, Kiwata, & Aoun, 2015; Li et al., 2016).

$$Re = \frac{Wc}{\nu} \qquad (4)$$

Where c is the blade chord length, ν is the kinematic air viscosity, and W is the resultant velocity to blade.

The architectural Model B1-B2 leads to the high C_p performance of the resultant velocity to the blade (W) and the light weight of Model B1-B2 can reduce the gravitational force that affects high Reynolds number. A higher Reynolds number enables better turbine performance. It is indicated that stronger torque is generated on the rotor for a greater Reynolds number, causing the enhancement of the lift coefficient for the blades (Li et al., 2016; MacPhee, & Beyene, 2019; Mishnaevsky et al., 2017).

Figure 6(b) shows the relationship between the tip speed ratio (TSR) and coefficient of torque (C_t), which displays almost the same trends as the trends in Figure 6(a). The Model B1-B2 represented also TSR value higher than Model A1-A2. Contrastingly, coefficient of torque (C_t) for Model A1-A2 was the highest when compared with others around 0.35 C_t.

Based on equation (1-2), the corresponding ratio between C_p and C_t is shown. The C_t in vertical axis 2 blades wind turbine the efficiency depends on the pith angle with a maximum of 18% C_p (Li et al., 2016). In the case of Darrieus (H-type), however, this investigation was performed β = 80° and stacked with Savonius rotor blade that can produce higher efficiency.

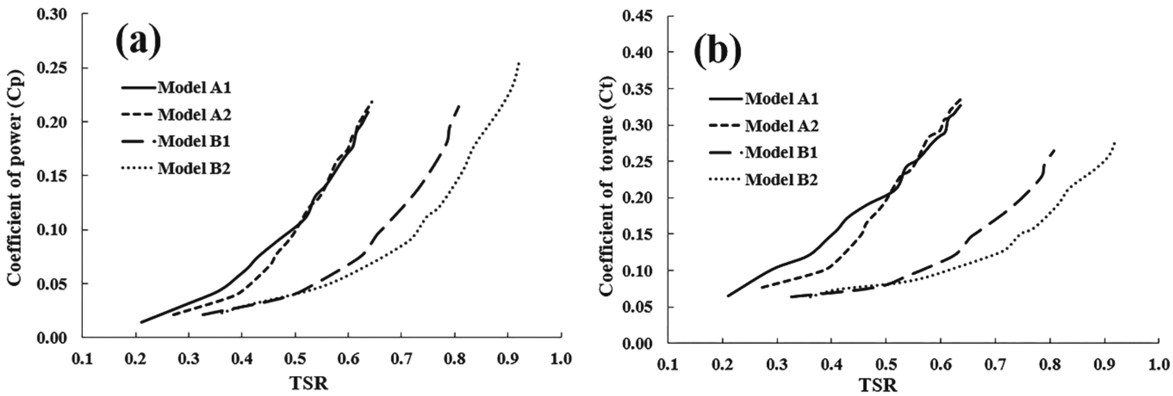

Figure 6 Vertical wind turbine behaviour for (a) the relationship between tip speed ratio and coefficient of power and (b) the relationship between tip speed ratio and coefficient of torque

However, the double-step rotor is obviously mentioned to be lightly superior to a related single-step turbine (conventional Savonius rotor) in both power characteristics and torque (Akwa, Vielmo, & Petry, 2012).

Conclusion

Experiments were carried out that focused on the cut-in of low wind speeds of around 2 m/s. Wind tunnel experiments were used for testing the VAWT rotor combined between the Savonius and Darrieus rotors. Both blades were switched between locations at upper-lower. The properties of the blades in the study were classified as 2 models. Performance investigations of combining Savonius-Darrieus rotors were also carried out with the same conditions to compare the 2 models. The effects of the weight and switching from 2 models were discussed with the rotation speed, torque value, coefficient of power (C_p) and coefficient of torque (C_t) at different velocities and tip speed ratios. The results from the study may be summarised as follows:

- In the present study, it was found that the position of both the Savonius and Darrieus types affected the performance of wind turbines. The Savonius was located at the upper position and Darrieus located at the lower position as Model A2. Model B2 showed higher performance than Model A1 and Model B1.
- The experimental results revealed that the weight of the wind turbine will become gravitational loads. The cut-in of the wind turbines

increases with the increasing weight of the wind turbine. The best start-up occurs at a low speed of 1.52 m/s as occupied to Model B2 due to Model B2 being fabricated from lightweight acrylic materials.

- The rotational speed (RPM) and torque value combined between the Savonius and Darrieus rotors for all 4 models increase with the increasing of velocity. Also, the coefficient of power (C_p), coefficient of torque (C_t) and no-load tip speed ratio increase with an increase of tip speed ratio (TSR).

Therefore, the Savonius was located at the upper position while the Darrieus was located at the lower position which allows it to start-up at low speeds and can also increase efficiency when using lightweight acrylic materials, such as Model B2. The Model B2 vertical wind turbine showed high performance during this study.

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