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# Conceptual design of small wind turbine blades with morphing ability

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## ABSTRACT

Stall control small horizontal axis wind turbines (under 250 kW) in general can efficiently generate power at high efficiency only at the design wind speed due to the fixed rotor blades. Major disadvantage of the non-movable blades is the reduced power production performance at wind speeds below and beyond the design speed. There is another point to consider. The stall control turbine may be designed to work efficiently at high wind speeds but these designs would suffer from the high cut-in wind speeds penalty which results in the turbine not producing any power at low to moderate winds. The high cut-in speed is a major problem for countries with generally low average wind speed such as Thailand. These results in a need for improving the pre-cut-in and post-stall performances of a stall control turbine. Hence, this research aims to achieve this improvement by introducing a morphing blade capability so that the stall control turbines can excel in their traditionally weak areas, i.e. lower the cut-in speed or extend the operation range under high wind speeds. This work assumes a use of shape memory alloy as actuators to enable wind turbine blade morphing capability to improve the performance the turbine by extending its operation range. The design of morphing blade begins by identifying a base airfoil as Clark-Y airfoil. Shape memory alloy technology is chosen as the morphing actuator because of (1) its compact size when compared to traditional actuator mechanisms such as electric motors, hydraulics and pneumatics and (2) the gapless blade surface during morphing. Results in power coefficient of conventional wind turbine and morphing have been compared, including the calculations of annual electrical power capacity. The results show that wind turbine with morphing blades is able to produce 2172.5 kW·hr/year or 24.8% in annual capacity which is higher than the conventional baseline wind turbine annual capacity at 1728.52 kW·hr/year or 19.73%. There is an increase of 444.0 kW·hr/year or 5.07%.

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## 1. INTRODUCTION

Horizontal axis wind turbine (HAWTs) can generally be classified into two types (1) pitch controlled and (2) stall controlled. In simple terms, the pitch controlled system refers to the movable (in rotation) turbine blades which enhance the turbine performance by continually optimizing the angle of attack between the blade and the relative flow to maximize the rotor torque. The pitch control system is only found in large HAWTs, usually with rated power production higher than 250 kW. With a blade length of 13.4 m and a diameter of 30 m. [J.P. Sayler & Associates, Consultants Ltd] This is because of the size limitation of the pitch control actuation system. Hydraulics or electric motors are usually used to provide torque for the blade longitudinal rotation. These mechanical are large and cannot physically fit into the wind turbine rotor hub. Therefore, it is very common that smaller HAWTs (under 250 kW) only feature stall controlled rotor.

Stall controlled HAWTs are wind turbines with fixed blades. The blade twist and chord length variation have been optimized for operation at a specific design condition, usually at the rated wind speed where it produces the maximum power. The stall control wind turbines clearly have advantages over the pitch control turbines when it comes to construction simplicity and maintenance costs due to fewer moving parts. However, the major disadvantage of the non-movable blade is the reduced power production performance at high wind speeds beyond the design speed. This is clearly illustrated in Fig. 2 The pitch controlled wind turbines with the rotatable blade mechanism are able to harvest the high power production at high wind speeds, i.e. higher than the design wind speeds up to the cut-out wind speeds.

Fig. 1 [Left] Picture of a 1.25MW wind turbine rotor hub showing a circular plan form connection between the hub and the blade where the pitch control mechanism is housed. [Right] Picture of 4kW rotor hub with a simple non-movable blade-hub connection

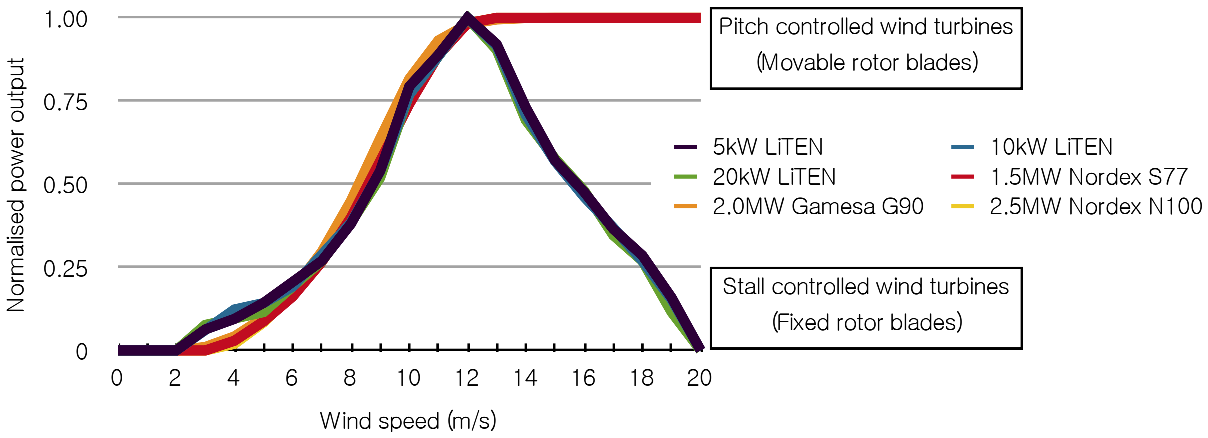

Fig. 2 Normalised Power curve comparison shows that the stall control turbines lose the opportunity to capture the high energy during strong winds. These curves have been normalized by its respective maximum power rating because only their characteristics are being compared.

The stall control turbine may be designed to work efficiently at high wind speeds but these design would suffer from the high cut-in wind speeds penalty which results in the turbine not producing any power at low to moderate winds. The high cut-in speed is a major problem for countries with generally low average wind speed such as Thailand. [Prupongpaiboon 2001]

This calls for a need in improving the pre cut-in of a stall control turbine. Hence, this research aims to achieve this by introducing a bi-stable morphing blade capability so that the stall control turbines can excel in their traditionally weak areas, i.e. lower the cut-in speed and compared capacity in term of annual energy production between bi-stable and conventional blade.

This study focuses on the aerodynamic designs of the two rotor blade profiles for use in a bi-stable three-bladed horizontal axis wind turbine. A 1kW model will be considered because it coincides with a future prototype construction plans and available resources. The feasibility of the study is assessed through the expected annual energy production increase of the bi-stable blade wind turbine when compared to a baseline case.

## 2. METHODOLOGY

This section describes bi-stable wind turbine rotor blade design methods and the morphing blade mechanism.

### *2.1 Wind turbine rotor blade aerodynamic design*

This work is based on the Clark-Y airfoil [Kang 2012] suggested that this airfoil is suitable for use on small wind turbine rotor blades because of its flat lower surface which makes it easy to install the morphing mechanism inside. The airfoil has a maximum thickness of 11.7% and 3.5% camber.

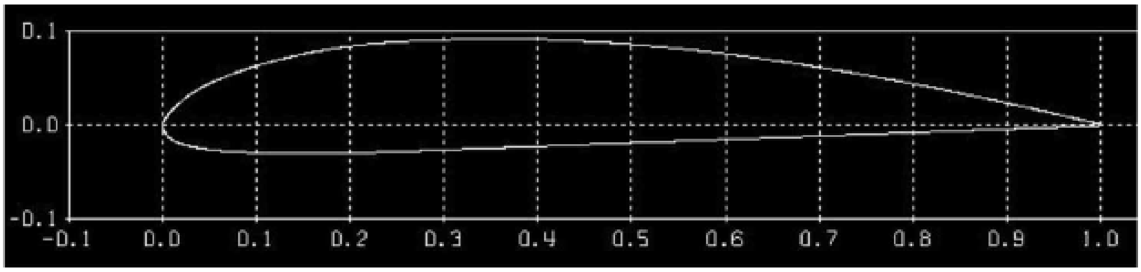

Fig. 3 Illustration of the base airfoil geometry (Clark-Y) plotted in XFOIL

The baseline design of a 1kW three-bladed horizontal axis wind turbine in this study makes use of simple untwisted rectangular planform blades for calculation simplicity. With a design wind speed, $U_{design}$ at 9.5 m/s as Thailand has an average wind speed of 6 m/s, [Prupongpaiboon 2001] the rotor blade general dimensions can be determined from the following equation.

$$P = C_P \eta \frac{1}{2} \rho \pi R^2 U_{design}^3 \tag{1}$$

A generic power coefficient ($C_p$) of 0.4, efficiency of generation ($\eta$) is 0.90 and density of air is 1.164 kg/m$^3$ are used in this study. Calculated to be radius of wind turbine is 1.33 m and chord at 0.03 m.

Next, the second rotor blade stable mode is to be designed at a lower wind speed in order to shift the 'peak' of the power curve to the left, or region of lower wind speed. This is done to maximize the available power during the lower wind speed days of the year. A range of second design wind speeds $5.5 \leq U_{design} \leq 7.5$ m/s have been considered. It is assumed that the rotor blade span is unable to increase, therefore, only the chord length and the twist angle can be changed.

Since the rotor blade swept area remains constant, it is important to increase the torque. Another parameter which will be optimized in this study is the trailing edge flap angle because this mechanism will help in maximizing the rotor torque at low wind speeds given that the swept area is relatively small. A range of flapping angle between $2° \leq \beta \leq 10°$ will be considered in this study.

The optimization and selection of second design wind speed and the trailing edge flapping angle is based on the maximum annual energy production of the morphing wind turbine. Fundamental 2-dimensional aerodynamic characteristics of airfoils with trailing edge flaps are determined using XFOIL and the power curve calculations are performed through MATLAB codes.

### *2.2 Mechanism of morphing airfoil*

This research aims to use small actuators to enable wind turbine blade morphing capability to improve the turbine performance by extending its operation range. Shape Memory Alloy (SMA) actuators are chosen because of (a) its compact size when compared to traditional actuator mechanisms such as electric motors, hydraulics and

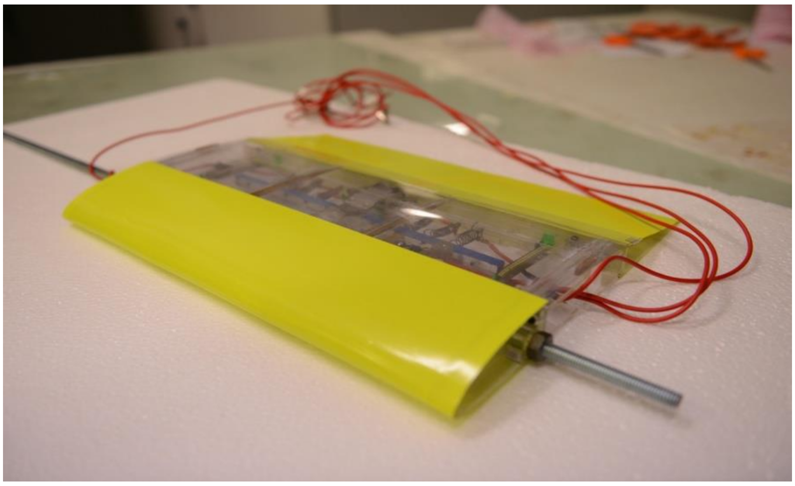

Fig. 4 A functional 40cm span with a Clark-Y airfoil [Chantharasenawong 2013] morphing wind turbine blade section with SMA actuated trailing edge flapping mechanism capable of bi-stable modes at $0^o$ and $20^o$ flapping angles

pneumatics and (b) the gapless blade surface during morphing. Several smart materials have been considered in the literature for use in a morphing blade for aeronautics application, based on a number of criterion such as responsiveness, structural rigidity, lightweight and low maintenance requirement. The possible materials range from ferroelectric materials (i.e. piezoelectric), variable theology materials (i.e. electro theological), shape memory alloys and shape memory polymers.

An SMA-actuated rectangular planform blade prototype has been constructed and tested (See Fig. 4). Several key findings have been reported in Ref. [Chantharasenawong 2013] such as:

- SMA actuators provide accurate morphing blade control with inaccuracy under 5% in 20-degree trailing edge lowering tests under working flow speed. Photographs during the test are shown in Figure 6. It can be concluded that the SMA-actuated mechanism is able to provide sufficient hinge moment for other trailing edge flap angles up to 20 degrees.
- Reasonably responsive wind turbine morphing blade control with 16 seconds and 6 seconds to flap down and flap up, respectively. Shown in Table 1.
- The mechanism was repeatedly tested to ensure that it is able to produce consistent results without failure, which it successfully completed.

Fig. 5 Successful demonstration of the SMA-actuated trailing edge flap lowering test under 15 m/s flow speed exhibits under 5% flapping angle inaccuracy when trailing edge flap is actuated.

Table 1 The actuator response time frequency distributions in both trailing edge deflection directions obtained from 10 actuation cycles show reasonably quick responses, i.e. averaging 16 seconds in the flap-down direction and 6 seconds in the flap-up direction.

| | Lowering flap | Raising flap |
|---|---|---|
| Starting angle | $0^o$ | $20^o$ |
| Final angle | $20^o$ | $0^o$ |
| Cycles | 10 | 10 |
| Minimum time taken | 15.0 seconds | 5.0 seconds |
| Maximum time taken | 18.0 seconds | 7.0 seconds |
| Average time taken | 16.2 seconds | 6.1 seconds |

## 3. RESULTS & DISCUSSION

### *3.1 Wind turbine power curves*

The first power curve as calculate power coefficient at each wind speed velocity of conventional wind turbine 1 kW due to designed to generate maximum power at wind speed 9.5 m/s. The conventional wind turbine can be created power coefficient 0.41 at wind speed 9.5 m/s and cut in speed at 2 m/s show in Fig. 6 dashed line.

The second power curve is wind turbine with morphing blade by used concept of trailing edge flap at designed to generate maximum power at wind speed $5.5 \le U_{design} \le 7.5$ m/s and a range of flapping angle between $2^\circ \le \beta \le 10^\circ$. Which This condition will be max power coefficient 0.403 at $\beta=2^\circ$ and $U_{design}=5.5$ m/s show in Table 2 therefore choose $\beta=2^\circ$ and $U_{design}=5.5$ m/s. Show in Fig. 6 dotted line.

The results of wind turbine 2 type will be increase power coefficient at each wind speed when generated advantage of wind turbine 2 type together between conventional wind turbine and wind turbine with morphing blade found at low wind

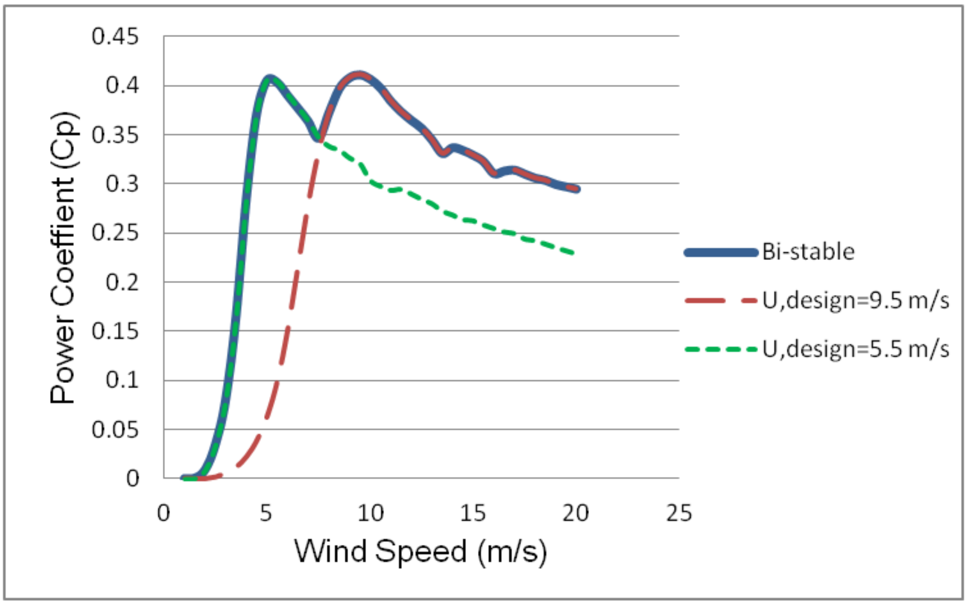

Fig. 6 The coefficients are various wind speeds of combine wind turbine between conventional wind turbine and wind turbine with trailing edge 2°

speed the wind turbine will be generated by wind turbine with morphing blade and high wind speed the wind turbine will be generated by conventional wind turbine. Which the results can increase power coefficient of wind turbine. Which intersection point is the speed that makes the change shape of airfoil. Show in Fig. 6.

### *3.2 Annual energy production*

Annual energy production is electricity consumption per year by compared with wind speed data of Thailand

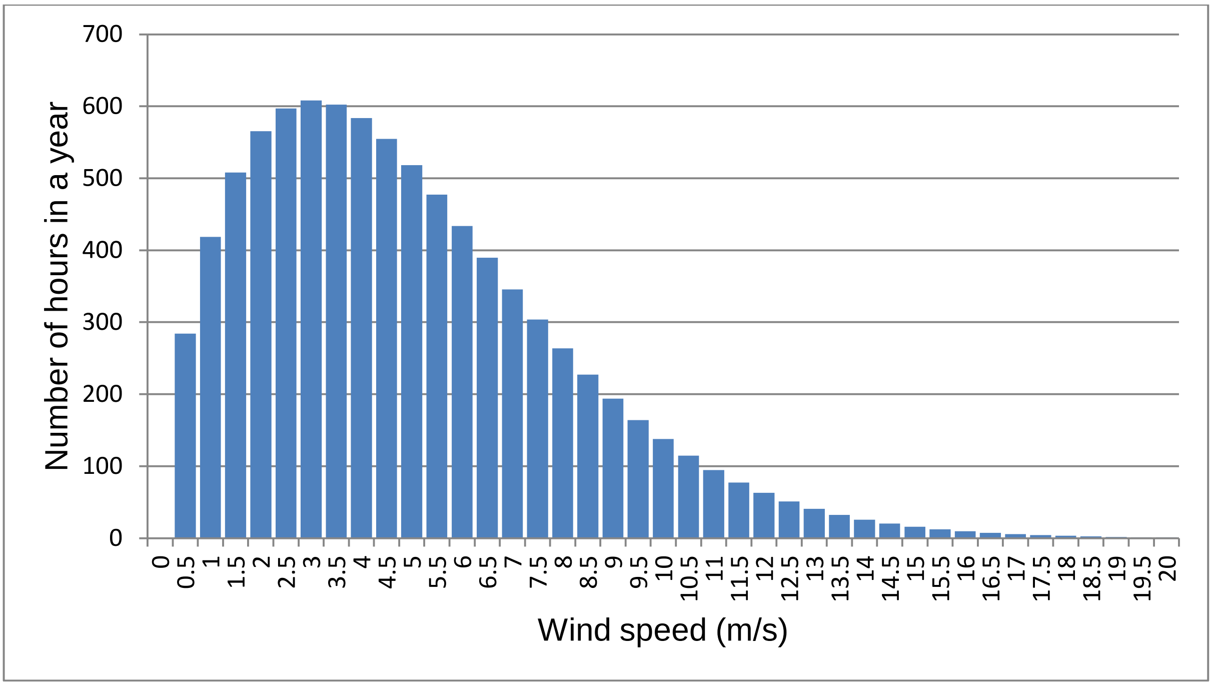

Fig. 7 Annual wind speed frequency distribution

Conventional wind turbine can generate power capacity per year is 1728.52 kW·hr/year or 19.73% of full generate power capacity per year. Calculation results in the annual production of turbine blades, which is a combine of the blades which is designed to speed the design wind speed is 9.5 m/s and designed blades at low design speed. Show in table 1.

Table 2 Capacity per year of wind turbine blades with morphing blade at design wind speed is 5.5 m/s.

| U,morph | Annual Electricity Production [kW.hr/year] | | | | | |
|---|---|---|---|---|---|---|
| | Trailing edge flap angle (degree) | | | | | |
| | 2° | 3° | 4° | 5° | 6° | 10° |
| 6 | 2020.5 | 2013.7 | 2014.0 | 2002.3 | 1994.1 | 2000.2 |
| 6.5 | 2086.9 | 2080.1 | 2078.7 | 2066.9 | 2059.4 | 2039.9 |
| 7 | 2138.1 | 2131.6 | 2120.2 | 2114.0 | 2108.6 | 2050.1 |
| 7.5 | 2167.3 | 2161.5 | 2147.1 | 2141.4 | 2136.0 | 2029.8 |
| 8 | 2172.5 | 2168.4 | 2149.5 | 2147.3 | 2141.3 | 1984.0 |
| 8.5 | 2158.5 | 2153.2 | 2125.7 | 2127.6 | 2127.1 | 1919.1 |

Table 3 Capacity per year of wind turbine blades at U,$_{morph}$ = 8 m/s

| Wind design speed (m/s) | Annual Electricity Production [kW.hr/year] | | | | | |
|---|---|---|---|---|---|---|
| | Trailing edge flap angle (degree) | | | | | |
| | 2° | 3° | 4° | 5° | 6° | 10° |
| 5.5 | 2172.5 | 2168.4 | 2149.5 | 2147.3 | 2141.3 | 2104.0 |
| 6 | 2172.5 | 2168.4 | 2149.5 | 2147.3 | 2141.3 | 2037.2 |
| 6.5 | 2158.1 | 2155.1 | 2144.7 | 2122.5 | 2114.2 | 2033.6 |
| 7 | 2133.2 | 2131.1 | 2119.8 | 2094.4 | 2078.0 | 1984.0 |
| 7.5 | 2096.3 | 2094.3 | 2080.1 | 2049.1 | 2029.5 | 1981.8 |

To simulate the conventional airfoil and morphing airfoil type Clark-Y with adapt angle of trailing edge at $2° \leq \beta \leq 10°$, $5.5 \leq U_{design} \leq 7.5$, $6 \leq U_{morph} \leq 8.5$. Which is a wind turbine at 2 design points. The first point use conventional airfoil and the second point use morphing airfoil by test for power coefficient and calculate annual energy production with compare power coefficient and wind speed data of Thailand. The results can be increase annual energy production which more conventional wind turbine only by wind turbine with morphing blade at trailing edge angle 2°, $U_{design}$=5.5 m/s, $U_{morph}$=8 m/s can be electrical is 2172.5 kW·hr/year which more conventional wind turbine can be electrical is 1728.5 kW·hr/year different to 444.0 kW·hr/year.

## 4. CONCLUSIONS

This paper found problem of stall wind turbine so increase efficiency of stall wind turbine by use bi-stable, combine between conventional blade and morphing rotor blade which use shape memory alloy as actuator. The bi-stable wind turbine can be electrical is 2172.5 kW·hr/year is equal to the annual 24.8% which more conventional wind turbine can be electrical is 1728.5 kW·hr/year is equal to the annual 19.73% different to 444.0 kW·hr/year is equal to the annual 5.07%. The further need more work on actuator mechanism and automatic control for a working prototype systems.

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