RECENT DEVELOPMENT OF VERTICAL AXIS WIND TURBINE: A PROMISING SOLUTION

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ABSTRACT

There is crucial need for clean and sustainable energy supplies nowadays. In recent years, wind energy is considered one of the most promising energy sources. Horizontal Axis Wind Turbines (HAWT) has been the widely practiced type, whereas Vertical Axis Wind Turbines (VAWT) is the lesser known type. To harvest wind energy at higher height, tremendous advancements have been progressed in the wind turbine technology with boosted size and capacity, as well as lighter components to achieve cost effectiveness and technical efficiency. Some of the recent findings revealed the potential of VAWT in future development. This paper aims to describe the recent development of VAWT and its merit over the conventional HAWT. The reasons driving the market to investigate the feasibility of using VAWT again are discussed, as well as the limitation of its future development. Finally, the feasibility of using VAWT in future wind power industry is evaluated. It is concluded that VAWT has significant development potential in future market of producing efficiency wind energy.

Keywords: *Aerodynamics; HAWT; Structural Dynamics; VAWT; Wind Engineering; Wind Power.*

1. INTRODUCTION

Wind Energy is considered one of the most promising energy sources (Islam *et al.*, 2013). Over the past decades, research studies of Horizontal Axis Wind Turbine (HAWT) and Vertical Axis Wind Turbine (VAWT) have been focusing on to maximise wind power output (Islam *et al.*, 2013). Figure 1 shows the typical configurations of HAWT and VAWT. Tremendous advancements have been progressed in the wind turbine technology in recent years with boosted size and capacity, as well as lighter components to achieve cost effectiveness and technical efficiency (Harte *et al.,* 2012). As such, it is worthwhile to compare the development of both systems in recent years and to evaluate the possible reasons driving the market to favour HAWT.

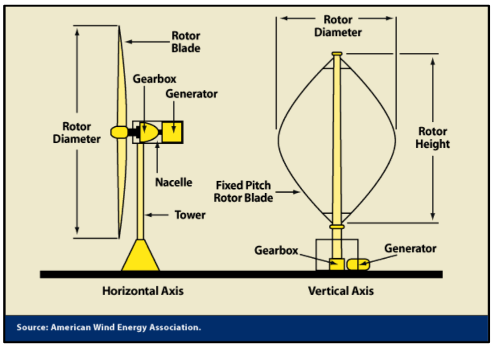

Figure 1: Wind Turbine Configuration
Source: American Wing Energy Association

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2. BACKGROUND

It is understood that Wind has been used as energy source long time ago. (Eriksson *et al.*, 2008). Approximately 900AD, the first windmills were used by Persians while this is in the form of VAWT. Then, both HAWT and VAWT have been developed and during 20th Century, HAWTs continued to develop where larger modern HAWTs were constructed (Islam *et al.*, 2013).

Today, the most common wind turbine is HAWT. By definition, the axis of rotation is along to the ground which is considered to be the horizontal axis. Basic rotation concept is presented in Figure 2a and 2b.

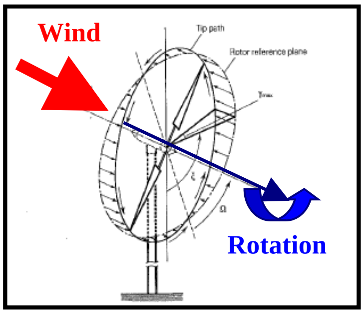

Figure 2a: HAWT Schematic Drg. 1

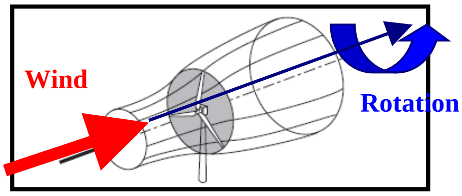

Figure 2b: HAWT Schematic Drg. 2
Source: Freris (1990)

Contrary to HAWT, Vertical Axis Wind Turbines (VAWT) is the axis of rotation to be along to the vertical axis. See below Figure 3a and 3b.

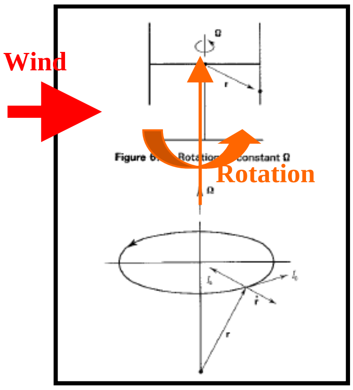

Figure 3a: VAWT Schematic Drg. 1 - Section

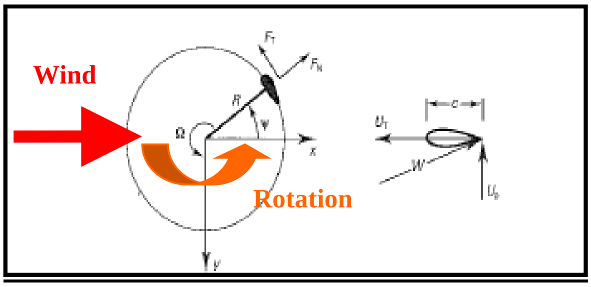

Figure 3b: VAWT Schematic Drg. 2 - Plan
Source: Freris (1990)

Under the category of VAWT, there are three different concepts, namely: Savonius Turbine, Darrieus Turbine and the H-Rotor. Refer Figure 4.

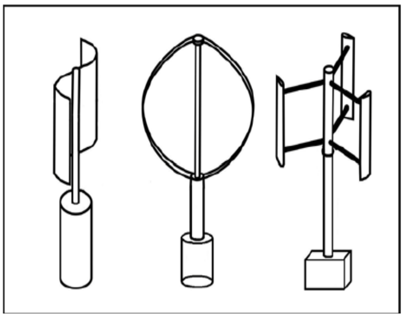

Figure 4:- Basic VAWT Configurations. Savonius Rotor (Left), Darrieus Rotor (Middle) and H-rotor (Right). In 1922, S.J. Savonius invented Savonius rotor where George Darrieus patented his Darrieus rotor in 1931. H-rotor is a form of Darrius type with straight blades instead of curve blades.
Source: Eriksson *et al.* (2008)

Basic wind power equation (1) is as follows:-

$$\text{Power (P)} = 0.5 \times Cp \times \rho_{air} \times A \times V^3 \qquad \text{(Eq: 01)}$$

where, ρ_{air} = Density of Air, Cp =Turbine efficiency, A = Swept Area (Wind projected area covered by the wind blade swept), V = Wind Velocity.

A power law profile (boundary layer) is used as an arithmetical approximation for wind velocity against height. Refer Figure 5.

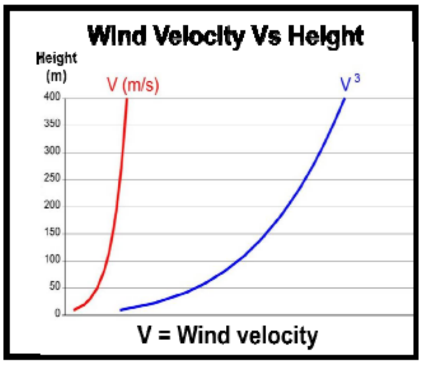

Figure 5: Wind Velocity (V and V^3) Against Height According to Boundary Condition

From Eq: 01, we can reveal that the wind power generation (P) is directly proportional to Cp, A and V^3 if we consider ρ_{air} is around 1.22kg/m^3.

Different type of wind turbines will have different value of Cp. According to Betz Limit (Freris, 1990), the maximum Cp value is 0.593 where this is the energy can be obtained from wind turbine under idealised condition. A more detail explanation of different Cp value for HAWT and VAWT will be discussed in later section.

On the other hand, if a wind turbine can provide a larger value for A and V^3, wind energy generation (P) can be higher. This is the reason why both HAWT and VAWT are aimed to be larger and higher in their development.

3. AIMS AND OBJECTIVES

This paper aims to describe the recent development of VAWT and its merit over the conventional HAWT. The reasons driving the market to investigate the feasibility of using VAWT again are discussed, as well as the limitation of its future development. Finally, the feasibility of using VAWT in future wind power industry is evaluated.

Objectives of this paper are as follows:-

- Identify advantages and disadvantages of HAWT and VAWT
- Evaluate the key reasons why HAWT is more common in the market
- Identify current obstacle of HAWT and limitation in future development
- Evaluate feasibility of VAWT in future development, particular those large scale wind turbines which is higher and larger in size.

The information of design data of recent HAWT and VAWT will be collected. They will be quantified for analysis to identify the advantages and disadvantages of each type of wind turbine. Key reasons driven the market towards HAWT will be evaluated and identification of current design obstacles of HAWT for further development. Potential of VAWT in future development will be discussed and finally, it is purposed to obtain conclusion that VAWT will be a promising solution in wind power industry to capture higher energy with higher height and swept area.

4. METHODOLOGY

There are several elements involved in the design and construction process for HAWT or VAWT whereas it is necessary to understand. To illustrate their relationship, an IDEF (0) model shown in Figure 7 is used.

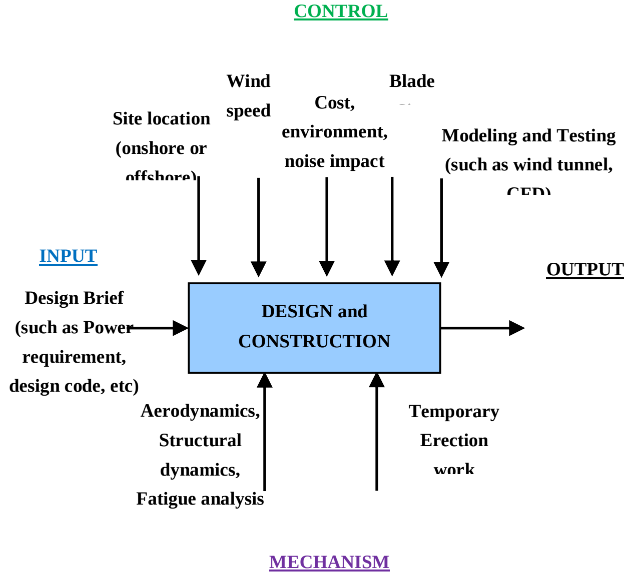

Figure 7: IDEF (0) Model

The process shown in IDEF (0) model is illustrated by a rectangular process (design and construction) that produces outputs from inputs where various mechanisms with difference controls.

However, in order to have more detailed description of the process, IDEF (1) model is demonstrated below (refer Figure 8) to show the relationship with Design and Construction as separate process.

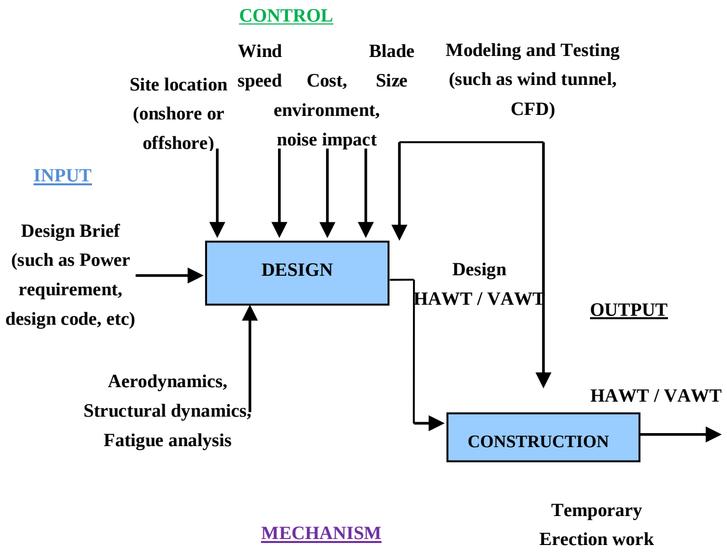

Figure 8: IDEF (1) Model

In the above IDEF (1) model, it is considered that the design and construction process are linked by a control – modelling and testing.

With the above understanding for process of HAWT and VAWT's design and construction and in order to answer research questions, the following work tasks are required;

- Literature review on relevant documents on the basic design principle of HAWT and VAWT. During this stage, key consideration in the field of aerodynamics, structural mechanics and dynamics and fatigue analysis of HAWT and VAWT are identified.
- Collection of data from published journal papers of the recent as-built HAWT and VAWT. These data can provide information on the consideration in terms of cost, environment and noise issue as well as the difficulties during temporary erection work.
- Analyse the information gathered to identify findings corresponding to research objective.

5. LITERATURE REVIEW

5.1. RECENT DEVELOPMENT OF HAWT AND VAWT

After oil crisis in 1973, many countries commenced their development programs for wind energy projects and to look for reliable renewable energy source in lieu of the conventional fossil fuel. In 1975, a 38m diameter two blades HAWT with rated power output of 100kW was constructed near Cleveland, Ohio of the United States. Subsequently, during 1970s to 1980s, a numbers of different multi-megawatt wind turbines (both HAWT and VAWT) were constructed and completed (Kirke, 1998).

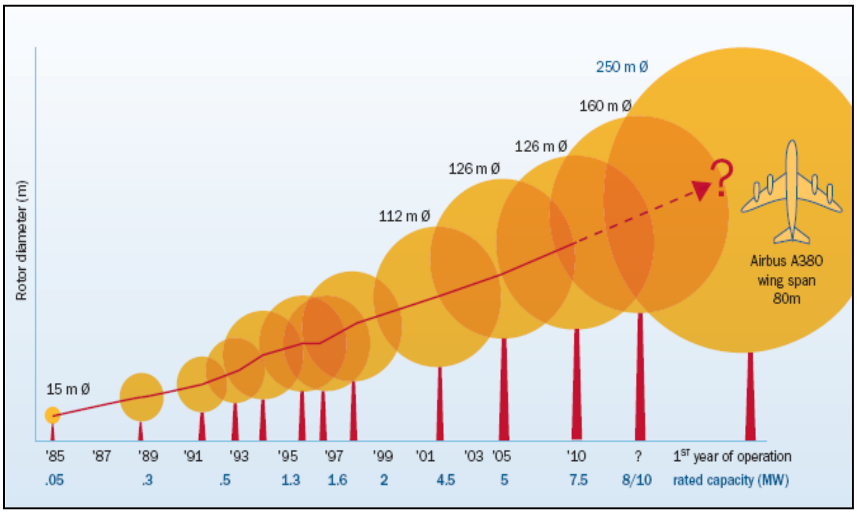

Figure 9: Recent HAWT Rotor Size
Source: http://1.bp.blogspot.com/-sr7ynn7H6Qo/T-H-d0nI8XI/AAAAAAAAAVtk/1hBcaNRv5hQ/s1600/wind20mwb.png

In 2007, the tallest HAWT (Enercon E-126) was built with height of 198m and blade diameter of 126m which can generate electricity up to 7 Megawatt (7MW). From published data, it is understood that study of producing blade length up to 100m long for HAWT has been carried out in the Sandia National Laboratories of the United States (Veers, 1984).

Figure 10: Enercon E-126

Several prototypes of VAWTs in the form of Darrieus were initiated by both Canada and the United States. The Eole, the tallest Darrieus VAWT was built in 1986 in Quebec of Canada (refer Figure 11). It can produce rated power output up to 4MW (Templin and Ranj, 1983).

Figure 11: The Eole, VAWT in Quebec of Canada

The Eole was operated until in 1993 due to a report of failure of the bottom bearing. On the other hand, in Sandia National Laboratories of the United States (refer Figure 12), numbers of different size of Darrieus VAWT were operated until in 1997, the last VAWT was shut down due to the problem observed in its foundation. Some others VAWT also reported to have fatigue problems of the blades even though the VAWT was operated efficiently (Berg, 1985).

Figure 12: VAWT in Sandia National Laboratories

In the 1980s, American company FloWind constructed a wind farm in the United States by using VAWT of Darrieus form (refer Figure 13).

Figure 13: Wind Farm under FloWind

In 1980s to 1990s, in the United Kingdom, H-rotor type was investigated and a 500kW VAWT H rotor was built in 1989 (refer Figure 14).

Figure 14: VAWT (H Rotor) in UK

Based on published information, in the 1980s, due to a poor wind energy market in USA, numbers of VAWTs' company were required to close and the development of VAWT was slow down thereafter.

It is clear that both HAWT and VAWT are developed in parallel initially while after few reported case of VAWTs' problem and less financial support and interest from investors, HAWTs received more attention and nowadays, most of the large wind turbines are in the HAWT form.

Eriksson *et al.* (2008) summarise of the differences between HAWT and VAWT is tabulated in Table 1.

Table 1: Summary of Main Difference between HAWT and VAWT

	HAWT	**VAWT (Darrieus)**	**VAWT (H- rotor)**
Blade profile	Complicated	Complicated	Simple
Yaw mechanism	Yes	No	No
Pitch mechanism	Yes	No	Yes
Central tower	Yes	No	Yes
Guy wires	No	Yes	Optional
Noise	High	Moderate	Low
Blade area	Small	Large	Moderate
Generator position	On top of tower	On ground	On ground
Blade load	High	Low	Moderate
Self -starting	Yes	No	Yes/No
Tower interference	Large	Small	Small
Foundation complexity	Extensive	Simple	Moderate
Overall structure complexity	Complicated	Simple	Simple

Source: Eriksson *et al.* (2008)

5.2. *AERODYNAMICS*

Based on Eq: 01 discussed in previous section, it is understood that the wind power generated (P) is directly proportional to the Cp value which is the turbine efficiency. This Cp value is the interaction relationship between the rotor and the wind. According to Betz Law (Freris, 1990), the maximum Cp value for an idealised wind turbine is 0.59. Different Cp value for HAWT and VAWT are shown in the following Figure 15.

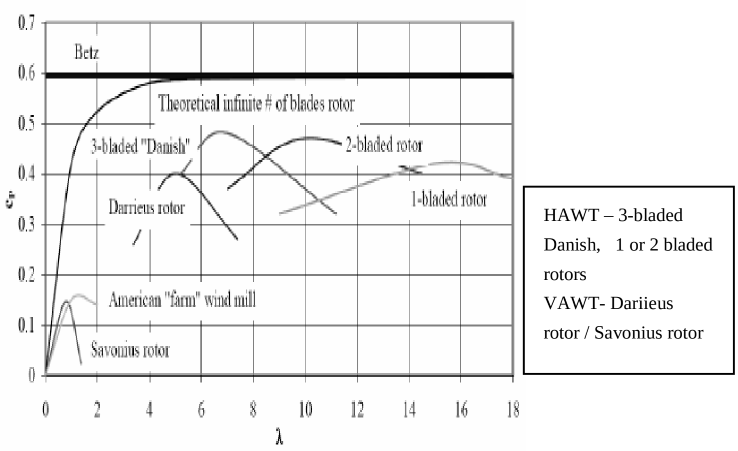

Figure 15: Cp –λ Curve for HAWT and VAWT
Source: Kirke (1998)

Cp is a function of the tip speed ratio λ which is defined as $\lambda = \omega R / \upsilon$ where ω is turbine rotational frequency, R is turbine radius and υ is wind speed.

For a HAWT, the CP value is usually between 0.40 and 0.50 while generally, VAWT's CP value is lower than HAWT.

However, recent study has revealed that VAWT's Cp value can be increased and to be close to HAWT (Hunter, 2009). It is considered one of the main breakthroughs in recent development of VAWT.

5.3. STRUCTURAL MECHANICS AND DYNAMICS AND FATIGUE

It is evident that major aspects of wind turbine performance are determined by the aerodynamic forces generated by the wind. These periodic aerodynamic forces are the source of fatigue load which affect the structural performance of both HAWT and VAWT. Wind turbines use airfoils to transform kinetic energy in the wind into useful energy. Airfoils are structures with specific geometric shape that used to generate mechanical force due to the relative motion of the airfoil and the surrounding air (Zhang, 2004). A typical airfoil shape for a blade is shown as follow Figure 16.

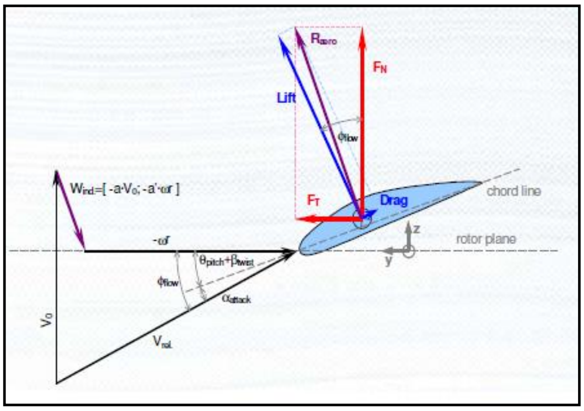

Figure 16: Typical Airfoil Shape of Wind Blade Showing the Lift and Drag Force
Source: Freris (1990)

5.3.1. HAWT

The blade of a HAWT is subjected to reversing aerodynamic forces at its root during its rotation along the horizontal axis in Figure 17. With this periodical loads act on the blade, the blade is considered susceptible to fatigue problem (Eriksson *et al.*, 2008). With the advances of today's material mechanics, nowadays, in lieu of using aluminium, these blades are made of composite material including carbon fiber or glass fiber. It is considered that the problem of fatigue in blades is reasonable managed in current HAWT. However, as size of blades increases substantially in the recent development, fatigue problem is still considered one of the major design constraints in HAWT.

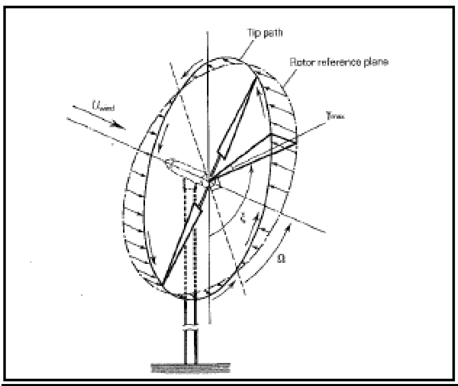

Figure 17: HAWT Showing Reversing Aerodynamic Forces at its Root during Rotation
Source: Freris (1990)

Apart from blade's aerodynamic forces and fatigue problem, HAWT is subject to tower interference and resonance problem during its operation (Eriksson *et al.,* 2008). Tower interference will eventually affect the performance of the turbines. However, for VAWT, the tower interference is considered less significant as the blades are located far away from the central tower.

Resonance will cause significant vibration and problem on the main tower and foundation, which is also the case for VAWT.

5.3.2. VAWT

Unlike the case of HAWT, VAWT's blade is not subject to a gravity induced reversing stress. However, VAWT is subjected to inherent torque ripple where this is caused by the changing of angle of attack between the blades and the incoming wind during the rotation along vertical axis. This torque ripple can affect the fatigue life of the drive train components and power output quality. On the other hand, the changing of angle of attack during each rotation will cause cyclic aerodynamic forces on the blades. Again, fatigue become a key issue to address during both design and construction stage of VAWT. Nevertheless, as mentioned before, with the advances of current material science by using carbon fiber to fabricate wind blades, fatigue issue can be reasonably controlled (Eriksson *et al.,* 2008).

5.4. CONSTRUCTION AND BLADE MANUFACTURE

Both HAWT and VAWT require a specific design of temporary erection procedures for the installation of blades. Blades of HAWT are attached directly to the central tower while blades of VAWT (H-rotor) are connected with central tower by a supporting arm. The supporting arms will add extra loading on the tower structure (Eriksson *et al.,* 2008).

The blades of HAWT require different shape along the length of the blade where it might be needed to be twisted under some circumstances. For VAWT (H-rotor), the blade can have same shape along the length so that the manufacturing process will be easier (Eriksson *et al.,* 2008).

5.5. NOISE IMPACT

VAWT is expected to have less noise than VAWT. This is due to the fact that a VAWT usually has tip speed ratio which is only half of the tip speed ratio of HAWT. As a result, there will be less aerodynamic noise.

6. ANALYSIS AND DISCUSSIONS

The followings are the research questions to be addressed in this paper.

- What are the advantages and disadvantages of HAWT and VAWT respectively?
- Why HAWT is the majority type of wind power in market in the past few decades?
- Has HAWT reached its design limit?
- Does VAWT demonstrate potential for future development?

The advantages and disadvantages of HAWT and VAWT can be summarised as follows.

HAWT's Advantages

- High turbine efficiency Cp value than current VAWT.
- Well established understanding and study on system performance, both in design and construction prospective.
- Adequate financial support due to more reliable system which has been proven.

HAWT's Disadvantages

- Blades approaching limit of viability as size increase.

- Yaw mechanism need. High cost required.
- Increase cost to handle fatigue problem as blade size becomes longer and larger.
- Higher noise level

VAWT's Advantages

- Wind from all direction can be captured and no yaw mechanism need.
- Simple blade airfoil shape design. Blades still have design capacity to cater for larger size VAWT.
- Less noise than HAWT.

VAWT's Disadvantages

- Low Cp value as compared to HAWT. However, some researchers claim that this may not be necessary true for modern VAWT.
- Self-starting problem as compared with HAWT. That means VAWT will not be able to start rotating. However, Kirke (1998) reported a type of VAWT can be self-starting and recent study also demonstrates it may not be necessary true and only happen under certain category.
- Inadequate understanding and study on system performance, both in design and construction prospective. Further study need to justify.
- Inadequate financial support due to lack of confident of system performance. Previous failure cases cause investor's hesitation to develop VAWT.

It is no doubt that in current markets, HAWT dominate the wind power industry. This is highly due to the fact that HAWT has shown a promising result over the last few decades where people do not have motivation to look for other solution. Also, HAWT tends to be more reliable due to the lesser problems as compared to VAWT. Therefore, more investment has been put into development of HAWT. In view of the technical consideration, both HAWT and VAWT has demonstrates their competence to harvest wind energy.

It is revealed that fatigue problem of blades of HAWT under the periodic aerodynamic forces with reversing stress acting on the root of the blades, will lead to the main limitation for increasing size for HAWTs. (Eriksson *et al.*, 2008)

Also, from Figure 9 showing HAWT's recent development from 1980s, it can observe that development of larger HAWT has been slow down recently. It reveals that it is due to difficulty to climb over the current height limit by HAWT. It is one of the main reasons why driven the researchers to go into VAWT again.

7. EVALUATION FOR THE FEASIBILITY OF VAWT IN FUTURE DEVELOPMENT

The technical advancement of VAWT lags behind that of the HAWT despite of the advantages of VAWT in terms of aerodynamic and efficiency. Nevertheless, stochastic nature of wind (e.g. changing its speed and direction) makes HAWT not favourable as compared with VAWT which do not need any unidirectional wind speed and no yawing mechanism is required. VAWT demonstrates that it is more effective in large scale development for harassing wind energy.

Islam *et al.* (2013) summarised that though the HAWT is well developed and adopted in the existing wind power industry, the recent R&D has shown that VAWT is more economical and efficient in respect to the required land use. In general, it is proved that using VAWT instead of HAWT on the same land area, it is likely to produce more than 10 times of wind energy. That means the power density of VAWT is considered substantially higher than that of the HAWT. These research findings were presented by Whittlesey *et al.* (2010). As such, with a same land area, it is feasible to produce more energy by using VAWT instead of HAWT. That will become one of the crucial considerations for future development of wind farm with VAWT.

Based on current research study on VAWT, it is proven that VAWT is a good solution in wind power industry due to its advantages to capture wind energy from all directions, as well as the recent advances in turbine efficiency Cp value for VAWT and more effective design of blades. It is understood that a multi-megawatts VAWT in UK's offshore area is about to construct (Hunter, 2009). Potential of VAWT in future development is considered promising.

8. CONCLUSIONS AND SUGGESTIONS

This paper presents a review on the recent development of HAWT and VAWT. Publications in major journals, books and research thesis revealed that both HAWT and VAWT have advantages and disadvantages. Basically, HAWT has been popular due to its higher Cp value, its reliable system performance owing to its well-established understanding and supporting research findings, and financial support and interest from investors, despite that some of the drawbacks like blade approaching limits of viability, high noise level and high cost to overcome fatigue problem.

On the other hand, VAWT is considered to have lesser attention due to several failure cases in 1980s to 1990s, as well as the shutdown of some VAWT's company, which eventually directed more focus and investment on HAWT in the past decades. VAWT has inevitably advantages in terms of its simplicity in blade airfoil shape and the ability to capture wind from all direction without the use of yaw mechanism. Recent advances in turbine efficiency Cp for VAWT has driven the market to investigate the feasibility of using VAWT in wind energy industry again. Moreover, recent research has demonstrated that higher power density of VAWT in respect to a given land area is also promising. It is expected that commercialised large scale VAWT will be in operation in the near future.

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