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ABSTRACT

Straight bladed fixed pitched vertical axis wind turbines (VAWTs) offer several potential advantages over the standard horizontal axis wind turbines which are now in common use worldwide. The purpose of this study was to determine the need for further research and develop on improved airfoil or blade characteristics for use on straight bladed fixed pitched VAWT. This need was demonstrated by the design and construction of an airfoil that was physically modeled and field tested. The test showed that asymmetric airfoils would enable SBVAWTs to self start.

INTRODUCTION

Wind is an abundant energy resource ultimately powered by the Sun. It is estimated that approximately 3% of the Sun's thermal energy is transformed into wind energy. Recent studies show that current wind technology operating only in Class 3 wind locations is capable of producing approximately 72 terawatts of electricity (Stanford Report, 2005). This is forty times the amount of electrical power annually consumed worldwide and this clean power source is just beginning to be tapped on a large scale.

Wind energy is developing into a major alternative energy source. Over 159,000 megawatts of wind generation were operational by the end of 2009 with 38,312 megawatts added in 2009 alone (World Wind Energy Association, 2010). The reasons for this growth are straightforward.

Wind is a vast energy resource which is clean and renewable. By its inherent nature, wind power has the potential to reduce the environmental impact on wildlife and human health. Improvements in power electronics, materials, and wind turbine designs allow production to continually lower the cost of wind generated electricity making it today economically viable compared with most other fossil fuels.

Most wind turbines are installed in locations where the minimum annual average wind speeds are between 14.3 and 15.7 mph. This range is known as Class 3 winds. The consistency and speed of these breezes are major factors in locating wind turbine farms.

MODERN WIND TURBINES AND THEIR LIMITS

The majority of wind turbine design currently focuses on the horizontal axis wind turbines (HAWTs). Today, more than 90% of wind turbines in use are of HAWT design (Vieira da Rosa, 2009). Modern HAWTs are currently favored for electrical generation for several reasons. First, the arrangement of the blades allows nearly their full area swept to always be interacting with the breeze. This maximum exposure to the wind improves the coefficient of performance (C_p) of modern HAWTs. Modern HAWTs have low blade solidity which is the ratio of blade area to the actual swept area. This aids the blades or airfoils in the production of lift. Though very successful, the mod-

ern HAWT is not without criticisms or weaknesses.

A very common objection to wind farm development is the rhythmic noise from the rotation of the blades. Sources of this noise can vary from trailing edge blade noise relating to turbulence to the effect of unsteady loading noise caused by the change in wind velocity which is due to the presence of the tower and mechanical noise from the gearbox and yawing mechanism (Wagner, Bareib, and Guidati, 1996). Empirical evidence shows that common large commercial HAWTs can output sound pressure levels ranging from 58 dBA to 109 dBA (Rogers, Manwell, and Wright, 2006). The lower end of the range is often just above ambient noise sound pressure levels in some rural environments and the sound pressure level drops off rapidly with distance.

A second common objection concerns the aesthetics of large HAWTs. Though this topic is subjective by nature, it is often a very important issue during the planning stage of wind farm development. Many landowners fear that their property values will decrease if a wind farm is built near their property. Part of this fear is reduced by the \$3,000-\$5,000 annual lease that many rural landowners receive per turbine installed upon their property.

Some criticism has been brought about wind technology and the danger to avian species. Much of this concern stems from early wind farm construction in California. During the late 1970s and early 1980s, some farms were unfortunately sited in migratory bird paths. In light of these past mistakes, guidelines have already been developed by most states (Association of Fish and Wildlife Agencies, 2007). Current statistics shows that avian deaths due to wind turbines are approximately 0.02% of all the avian killed by other human built structures in the nation (Sagrillo, 2003). Massive construction of wind turbines nevertheless, have to be done carefully in order to protect wildlife.

Finally, there are three technical issues that demonstrate the limitations point of HAWT design. First, HAWTs cannot operate in high winds. Generally, the large turbines must yaw or turn their blades out of the wind and apply a brake when wind speeds reach above 25 m/s or about 55 mph. Unfortunately, the power available in any wind is directly proportion to the velocity of the wind cubed so many large turbines are unable to harness this power. HAWTs operate best on rolling hills, in mountain passes, or offshore where there are few obstructions. HAWTs are not designed for the turbulent winds found in urban environments. Finally, the size of the HAWT is reaching an upper limit. Massive 5 MW wind turbines with blade diameters of 126 m (over 400 ft) currently hold the title as the largest wind turbines. Though this is not the maximum structural or material limit, an end is in sight (Marsh, 2005). It is doubtful that reliable 10 MW HAWTs will ever be built. In light of all these criticisms and disadvantages, a renewed interest has been shown in vertical axis wind turbines, VAWTs.

VERTICAL AXIS WIND TURBINES

Vertical axis wind turbines (VAWTs) are the lesser known type of wind turbine. In VAWT designs, the air scoops or airfoils rotate perpendicular to the direction of the wind. As Gipe (2004) notes, there are two principle designs of VAWTs, the Savonius type and the Darrieus type though there are several configurations of the Darrieus type. Some of these Darrieus configurations are the focus of current research.

VAWTs were first recorded about 2,200 years ago in ancient Persia and were primarily used to grind grain (Cheremisinoff, 1978). In more recent times, the Finnish engineer S. J. Savonius created his first VAWT in 1922 (Peace, 2004). A typical Savonius design uses two S-shaped blades or cups for the rotor though some versions often incorporate more blades. Johnson (1985) writes that Savonius rotors are primarily drag turbines since their tip speed ratio is

Figure 1: A Homemade Savonius Wind Turbine (Courtesy of authors)



generally less than 1. Figure 1 shows a student built Savonius wind turbine.

According to Johnson (1985), a well built Savonius style wind turbine has a coefficient of performance of around 0.30 which is considered useful and reasonably efficient but its low tip speed ratio makes it better suited for the operation of mechanical pumps. Savonius VAWTs have two advantages in that they are simple and inexpensive to construct and are self-starting, even in low wind speeds.

In 1931, Georges Darrieus patented his VAWT in the United States (Bernhoff, Eriksson, and Leijon, 2006). Instead of cups catching the wind, the Darrieus model uses either two or three curved or straight blades which have a cross section similar to an airplane wing. Because of the wing profile, the Darrieus turbine is a lift producing machine. The blades of a traditional Darrieus turbine are curved and joined together at the top and bottom while being bowed outward in the middle. This shape is called a troposkein, which is Greek for turning rope (Johnson, 1985).

There are other forms of Darrieus wind turbines, notably the H-rotor design. The H-rotor Darrieus is the most common configuration of a straight bladed vertical axis wind turbine (SBVAWT). The "H" rotor received its name due to

the single horizontal arm supporting its two or more blades (Berg, 1996). The H-rotor may play a central role in developing wind energy. Figure 2 shows a modern H-rotor Darrieus wind turbine.

VAWT ADVANTAGES

VAWTs have several advantages which are just now beginning to be utilized. Islam, Fartaj, and Carriveau (2008) note that fixed pitch SBVAWTs are among the simplest types of wind turbines in existence. The airfoils of a SBVAWT are often uniform in cross section and do not require the extensive machining associated with HAWT blades. This simplifies airfoil design and construction. Most VAWTs have a low cut-in speed so that they produce at least a little electricity in low wind speeds. Many VAWTs have a tip speed ratio of only 2 to 3 which equates to some useful power production but with less noise generation.

Because VAWTs can intake wind from any direction, they can operate in turbulent and variable wind conditions far better than HAWT designs (Berry, 2009). In fact, VAWTs can often operate in higher wind speeds than their HAWT counterparts which equates to greater energy generation under these conditions. These advantages have led both designers and politicians to consider adding VAWTs to urban environments (Ragheb, 2008). VAWTs often have their gearbox and electrical alternator located near the ground which facilitates easier maintenance. Some new VAWT designs have a coefficient of performance approaching 0.40 and allow for greater turbine density per parcel of land (Allan, 2007). Marsh (2005) notes that new H-rotor VAWT designs may also break the 10 MW barrier as the orientation of the blades coupled with modular manufacturing techniques allow VAWTs to be constructed larger than HAWTs. However, there are reasons why VAWTs have not seen more widespread use in wind farms.

Figure 2: A Modern H-Rotor Darrieus Wind Turbine (Courtesy of Shaghai Aeolus Windpower Technology, LTD.)



VAWT DISADVANTAGES

Efficiency still is a major drawback to the use of VAWTs in commercial power production. State of the art HAWTs can realize coefficient of performance (C_p) values approaching 0.50 while the best VAWTs see C_p numbers a little better than 0.40. Johnson (1985) notes that most VAWTs average C_p values in the 0.30s. Secondly, VAWTs have traditionally have not been located on towers. This often limits the turbine's access to higher winds and thus higher electrical production. Historically, VAWTs cost more to operate and maintain than HAWTs. The Flo Wind Company supplied a fleet of several hundred VAWTs located in the Californian mountain passes of Altamont and Tehachapi which operated for 20 years before maintenance costs caused the machines to be retired (Sagrillo, 2005). Finally, traditional Darrieus rotors are not self-starting under most wind conditions and the manufacture of their blades is a challenge because of the complex shape which adds expense to the turbine. Research and development of H-rotor Darrieus models is seeking to overcome both the self-starting and manufacturing issues of the traditional "eggbeater" style.

SELF-STARTING

The (Darrieus) VAWT is not self-starting and typically uses the generator as a motor to spin the blades up to operating speeds (Berg, 1996). Exceptions do exist as Darrieus turbines can self-start under certain conditions. The principal issues affecting self-starting capabilities are the electromechanical load upon the VAWT and the shape and number of airfoils.

Darrieus wind turbines have difficulty in self-starting in most normal wind regimes. However, evidence shows that a Darrieus turbine using fixed geometry symmetrical airfoils can self-start in the field during atmospheric gusting (Dominy, Lunt, Bickerdyke, and Dominy, 2006). Evidence shows that lightly loaded VAWTs equipped with symmetrical, NACA (National Advisory Committee for Aeronautics) 0012 airfoils will self-start in wind speeds under 10 m/s, 22.4 mph (Dominy et al., 2006).

As Tangler (2000) notes, the constant chord VAWT blades adversely affect blade efficiency and self-start capability. Darrieus type VAWTs have historically used symmetric airfoils from the

NACA 4-digit series, mostly NACA 0012, 0015, and 0018 which were developed for aviation applications (Islam, Fartaj, and Carriveau, 2008). These airfoils were used because there is much performance data for them. However, the main problem with using these symmetric airfoils is their low starting torque at low speeds (Islam, Fartaj, and Carriveau, 2008).

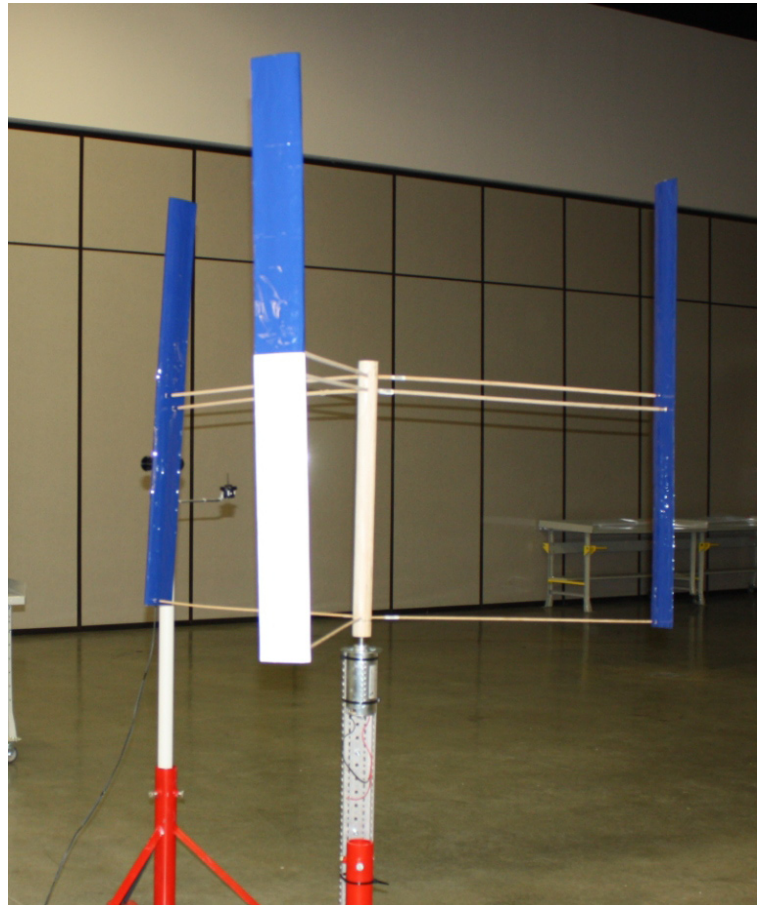
Research into new airfoils for VAWT applications is increasing. The general direction for Darriues H-rotor design points to using asymmetric airfoils in place of symmetric airfoils. Islam, Fartaj, and Carriveau (2008) state that it is better to use a high lift and low drag asymmetric thick airfoil for low speed operation typically encountered by SBVAWTs. These thick airfoil shapes have several advantages for smaller SBVAWTs including improved performance and increase in starting torque (Islam, Ting, & Fartaj, 2007). Continued research and development with thick airfoil shapes is warranted with a focus upon developing a self-starting SBVAWT.

MATERIALS

Airfoil materials for SBVAWTs must be judiciously chosen because wind turbines operate under a variety of forces and weather conditions. Berg (1996) states that wind turbines are fatigue critical structures subjected to combinations of wind, gravity, and gyroscopic loadings. At rotation rates of 30-60 rpm, the turbine blades must withstand at least 10^9 cycles during a 30 year lifetime which is 100 to 1000 times more cycles than a typical transport aircraft is designed to withstand.

Aluminum blades fabricated by extrusion and bending have often been used on VAWTs. Though reasonably inexpensive to manufacture, aluminum is not the best choice for VAWT blades. The main problem with using aluminum alloy is its poor fatigue properties and its allowable stress levels in dynamic applications decrease rapidly at increasing number of cyclic stress applications (Islam, Ahmed, Ting, and Fartaj, 2008).

Figure 3: An Experimental H-Rotor Darriues Wind Turbine (Courtesy of the authors.)



Wood is a better choice for VAWT blades. Many smaller, homebuilt HAWTs use wooden airfoils. As a building material, wood is readily available and has good fatigue properties as well as a relatively high strength-to-weight ratio but has moisture stability issues (Islam, Ahmed, Ting, and Fartaj, 2008). It is easily shaped and wood can be coated to prevent moisture penetration. It is a good candidate for small, experimental VAWT airfoil research.

Fiberglass composites or fiber reinforced plastics are another possible material for VAWT airfoils. These composites have low density, good mechanical properties, excellent corrosion resistance and versatility of fabrication methods (Islam, Ahmed, Ting, and Fartaj, 2008). Fiberglass composites already see widespread in HAWT blades where their strong performance makes

them the material of choice. Fiberglass composites are another strong candidate for small, experimental VAWT research.

CONCLUSIONS AND SUGGESTIONS

The superior capabilities of VAWTs described have shown the need for additional applied research in the design characteristics of various VAWTs. In addition, the authors hope this research will facilitate better SBVAWT designs for future commercial applications.

A small working model of a SBVAWT outfitted with experimental airfoils was constructed. This SBVAWT was designed to produce an electrical output of about 100 watts. A review of the current literature has shown a possible design using thick asymmetric blades. Blades were manufactured using wood

and plastic film and the resulting airfoil was field tested under various wind speeds and electric loads. The results of this test showed that under standard wind and load conditions the SBVAWT self-started as needed to become a viable VAWT design process.

It also appears that VAWTs equipped with the asymmetric airfoils optimized for self starting and particular aerodynamic regimes could be utilized in regions of low or turbulent air. This could create the opportunity for wind turbines in more urban areas. A VAWT has more acceptable aesthetics and can operate in turbulent air that would exist in an urban environment. Though low wind speeds produce low power, properly designed VAWTs show cut in or start up at low wind speeds. Some energy production at these low speeds adds to the attractiveness of the design. Figure 3 shows a small working model of a SBVAWT constructed as part of this research.

Finally, the authors believe that in Class 2 (12.5–14.3 mph) wind locations, the small VAWTs researched here may become the choice as low speed wind turbines are adopted in urban residential and commercial installations.

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