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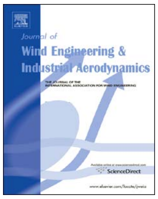

Analysis and optimal design of wind boosters for Vertical Axis Wind Turbines at low wind speed

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ABSTRACT

Vertical Axis Wind Turbines (VAWTs) are usually chosen for urban areas where local average wind speed is low. However, standalone VAWTs are unable to generate mechanical power satisfactorily for best practice. This study presents analysis and optimal design of airflow controlling equipment for a VAWT, which is called a wind booster. The wind booster is proposed to be implemented with a VAWT in order to not only harvest energy with low availability at low wind speed, but also enhance performance of the VAWT at high wind speed. Particularly, the wind booster comprises a number of guide vanes, which are mounted around a VAWT. The guide vanes direct wind to impact VAWT blades at effective angles while passages between each guide vane are arranged to accelerate wind. The guiding and throttling effects of the wind booster are able to increase angular speed of a VAWT, leading to an increase in mechanical power of the VAWT. Optimal solutions of number, shape, and leading angle of guide vanes are determined by maximizing the coefficient of power. The proposed methodology can be generalized to determine optimal wind boosters for other types and dimensions of turbines from this study.

1. Introduction

In many accessible areas, such as the central region of Thailand, the average wind speed is relatively low, approximately 2–4 m/s at a height of 40 m, while wind direction changes over time due to many high-rises and obstacles (Quan and Leephakpreeda, 2015). Vertical Axis Wind Turbines (VAWTs) are preferable in terms of compactness and economic feasibility to operate at low wind speed in any wind direction. However, standalone VAWTs do not yield the most effective power conversion due to limitations of harvesting wind energy with low availability at low speed. In turn, various designs and techniques have been proposed to improve the energy conversion of VAWTs. For example, Dabiri (2011) enhanced power density via counter-rotating VAWT arrays while Shaheen et al. (2015) arranged diverse VAWT clusters with different numbers and patterns. In (Kim and Cheong, 2015), the aero-acoustics technique is indirectly utilized to lower energy loss due to noise in a Savonius VAWT. Performance of mechanical components was experimentally investigated for strengthening power generation (Hossain et al. 2007). It was reported that a twisted bamboo rotor had high potential compared to conventional blades (Saha, 2009). A magnetic levitation bearing system was used in successfully reducing vibration and countering torque (Kumbernuss et al., 2012). Butbul et al. (2015) developed novel flexible blades for VAWTs according to wind conditions. Additionally, CFD analysis is effectively applied to investigate mechanical performance of VAWTs (Mohamed et al. 2015, Wekesa et al. 2015; Lee and Lim, 2015). In designs, Takao et al. (2009) developed a directed guide vane row so as to capture a wind stream in a single direction while Chong et al. (2012) developed omnidirectional guide vanes. Pope et al. (2010) used numerical analysis to determine the operating angles of stator vanes for a VAWT. Ohya and Karasudani (2010) developed a shrouded horizontal axis wind turbine system called “Wind-lens turbine”. Wind can be speeded up by a shaped passage. Although those devices can capture wind, arrangements of guide vanes are not designed for best practice in those studies.

In this work, a wind booster is proposed for CFD-based analysis and optimization in order to improve mechanical power of VAWTs. With guide vanes, the wind booster can regulate flow direction and accelerate wind from any direction so as to yield the most effective impacts on VAWT blades. Optimal design of the wind booster leads to an increase in mechanical power, which is higher than standalone VAWTs.

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Nomenclature

Symbol	Definition
A	Swept area (m^2)
C_P	Coefficient of power
$\hat{C}_P$	Peak value of coefficient of power
f	Objective function
n	Number of design variables
P	Wind power (W)
P_T	Power output of vertical axis wind turbine (W)
r	Radius of vertical axis wind turbine (m)
T	Torque of vertical axis wind turbine (Nm)
v	Wind speed (m/s)
x	Design variable
α	Leading angle of guide vane (degree)
β	Number of guide vanes
δ	Step length
ε	Acceptable tolerance
λ	Tip speed ratio
ω	Angular speed (rad/s)
ρ	Air density (kg/m^3)
VAWT	Vertical axis wind turbine

2. Methodology

In this section, a power analysis of a VAWT is presented to describe efficiency of a VAWT, which is defined as the coefficient of power, with/without a wind booster. Conceptually, the coefficient of power is an inherent characteristic of a given VAWT. It represents the ratio of partial amount of wind power captured by the VAWT to total amount of wind power when wind blows through. Therefore, it can be altered after installing a wind booster where optimal choices of the wind booster can yield a maximal coefficient of power.

2.1. Power analysis of VAWT

To understand the proposed methodology, CFD analysis of a VAWT coupled with a specially-designed wind booster are performed, in order to analyze effects on air streams that lead to an increase in the overall angular speed of a VAWT at low wind speed conditions of 1–8 m/s. The concept for designing a wind booster is not only to guide wind to the blades of a VAWT, but also increase wind speed, before engaging the VAWT. The guide vanes with curve-sided triangle shape, as shown in Fig. 1, are designed to direct air flow to blades of a Savonius VAWT, which has a lower cut-in wind speed than a Darrieus VAWT. The proposed methodology can be generalized in determining optimal wind boosters for other types of VAWTs at low wind speed. The guide vanes are arranged to throttle air flow for increasing wind speed. Since wind can blow in all 360 degrees of a VAWT, the blades of guide vanes are mounted around the VAWT. The upper and lower rings are used to fix all the guide vanes at certain positions around the VAWT.

Fig. 2 shows the schematic diagram of air flowing through the VAWT equipped with the wind booster. The air at region A flows along a positive X axis through the wind booster. The guide vanes lead the wind to the VAWT blades at region B. The VAWT blades are effectively pushed by the wind in this region. Also, the guide vanes prevent the wind from countering rotation of the VAWT at region C. The passage between the two guide vanes throttles the wind in order to increase the wind speed. The wind speed at region B is higher than region A.

Actually, there is another conventional method, which is able to increase power output of a VAWT by enlarging the size of a turbine. However, the reasons to increase power output by boosting wind speed are:

1) Wind power is proportional to wind speed raised to the three power; therefore, increasing wind speed can greatly multiply the power output of a VAWT compared with an increase in size of the VAWT. The wind power can be expressed as (Quan and Leephakpreeda, 2015):

$$P = \frac{1}{2}\rho A v^3 \tag{1}$$

2) This approach does not require a large wind turbine, which means savings in both cost for materials and space for installation. Also, it may be workable at low wind speed due to easy start-up from minimal inertia.

Generally, the power output of the VAWT is determined as:

$$P_T = T\omega \tag{2}$$

Wind energy is the kinetic energy of air, which is partially recovered, by the VAWT. In other words, the power output of the VAWT cannot be entirely recovered for mechanical power. The coefficient of power is known as the fraction of the power output extracted from the power in the wind by the VAWT. In the theory of Betz, the coefficient of power is always not greater than 16/27 (0.59) (Abea et al. 2005). This inherent characteristic of a given VAWT can be used as efficiency of the VAWT. The coefficient of power is defined as (Kim and Gharib, 2013):

$$C_P = \frac{P_T}{P} \tag{3}$$

In wind power analysis, the coefficient of power is usually presented as a function of the tip speed ratio. The tip speed ratio is the ratio of the speed of the ending tip of the VAWT blade to the wind speed. It can be written as:

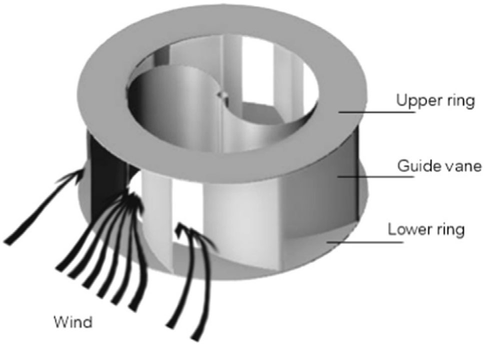

Fig. 1. Schematic diagram of VAWT and wind booster.