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Starting performance effect of a truncated-cone-shaped wind gathering device on small-scale straight-bladed vertical axis wind turbine

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ABSTRACT

In order to improve the starting performance of straight-bladed vertical axis wind turbine (SB-VAWT), an innovative truncated-cone-shaped wind gathering device (WGD) which could be installed up and down of the rotor was proposed to collect more incoming flow and increase wind speed. The main object of this study is to research the starting performance effects of the main structural parameters of the WGD on small-scale SB-VAWT. The studied parameters of the WGD included the cone angle, height and the distance to rotor. Based on the method of quadratic rotary orthogonal combination design, starting torque performance effects of the three parameters of WGD on SB-VAWT were researched by numerical simulation firstly. Two better structural parameter combinations of WGD were obtained. The static flow fields around the rotor with WGD were calculated. Furthermore, the model of the two kinds of WGD were designed and made. Wind tunnel tests were carried out on the static torque characteristics, rotational speed performance from static condition to stable rotational condition and the power characteristics at different tip speed ratios. According to the results, the new WGD proposed in this study was proved to be effective for both the static and dynamic performance improvement of SB-VAWT. This research can provide a reference for the study of optimum WGD for improving the performance of SB-VAWT.

1. Introduction

Benefiting from the rapid progress of large-scale wind turbine and wind farm, the small-scale wind turbine which can be used for distributed generation and off-grid wind power market has also received more and more attention recently [1]. However, there are some disadvantages of small-scale wind turbine comparing with large-scale one, such as small swept area of rotor which cannot receive more wind, difficulty of starting at low wind speed, affected by wind speed and direction easily, etc. These problems become the main obstacles for the development of small-scale wind turbine [2]. In general, wind turbine can be divided into Horizontal Axis Wind Turbine (HAWT) and Vertical Axis Wind Turbine (VAWT) according to the position of rotor axis. Although the HAWT is the most popular type in the world now, there is resurgence of interests in VAWT by researchers recently due to its characteristics of independence from wind direction comparing with the HAWT [3,4]. The VAWT can be thought as a good choice for the small and middle-scale wind power market. Despite many types of VAWT, the Straight-bladed Vertical Axis Wind Turbine (SB-VAWT) is the most recognized and widely researched now as a kind of Darrieus type VAWT for the advantages of simple design and configuration, lower cost and independence from wind direction [5–9]. It can be considered that the SB-VAWT is suitable for serving to the off-grid small-scale energy system which is one of the most important renewable energy resources for the people living in urban area and countryside.

However, based on the past researches, the power performance of SB-VAWT is rather lower than the propeller type HAWT and it has disadvantage on the starting performance under low wind speed. Many efforts have been made to study the ways on its performance improvement. The research methods can be summarized as mainly two ways [1]:

(1) By developing new rotor structure or blade airfoil with better aerodynamic performance;
(2) By adding additional device to increase the rotor performance, such as combining the SB-VAWT rotor with other kinds of drag type rotor or adding Wind Gathering Device (WGD) to collect more wind and increase wind speed into rotor.

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Nomenclature

Acronyms

HAWT	horizontal axis wind turbine
VAWT	vertical axis wind turbine
SB-VAWT	straight-bladed vertical axis wind turbine
WGD	wind gathering device

Symbols

C_p	output power coefficient
C_{ts}	static torque coefficient
C_{ats}	average static torque coefficient
T_s	static torque
T_{as}	average static torque
P	output power
λ	tip speed ratio
N	blade number
R	rotor radius
h	blade height
c	blade chord
θ	azimuth angle of rotor against wind
α	cone angle of WGD
H	cone height of WGD
ΔL	distance to wind turbine rotor
l_1	inner cone plane diameter of WGD
l_2	outer cone plane diameter of WGD
U	wind velocity

In view of the difficulty for the first approach, many researchers focused their efforts on the second method and some examples are introduced here. For the researches on combining with drag type rotor, as the most famous drag type VAWT, Savonius rotor is often used to be added in the rotor of SB-VAWT to increase its starting performance [10]. Although the improvement of starting performance by adding Savonius rotor is obvious, the power performance at high rotational speed is greatly affected. The reason is mainly because that the Savonius rotor will be turned into a load when its tip speed ratio becomes larger than unit. For the researches on adding WGD, most of researchers set up some different kinds of guide vanes around the rotor along with the wind direction. Numerical simulations and wind tunnel tests were carried out on the starting performance, power performance and flow field effects of guide vane on rotor [11–14]. According to the study results, the power performance of rotor with WGD can be increased in different degree. However, an important point should be noted that the size of the rotor with WGD becomes so large along the wind direction so that it gives larger thrust and drag force on the rotor than that without WGD. The requirements for structural strength and reliability of rotor with WGD become very high. Moreover, the setup of WGD should be detailed researched for that the characteristics of independence from wind direction for SB-VAWT must be considered.

Referencing the past researches, a new kind of wind gathering device is proposed in this study which is different from the past studies [15]. Fig. 1 shows the simple concept of a SB-VAWT rotor with this WGD. It is designed as a truncated-cone-shaped structure installed up and down of the rotor, instead of encircling the rotor along with the wind direction which is the popular type designed by past researches mentioned above. The main advantage of this WGD is that it can increase the wind speed from all wind directions. Furthermore, it will not need to take space along the wind direction so that the whole rotor structure will not be suffered huge thrust and drag force which is the biggest difference from the WGDs researched in the past.

To check the effectiveness of this idea, the main object of this study is to research the starting performance effects of the main structural parameters for WGD on a small-scale SB-VAWT. The studied parameters of this WGD included cone angle (α), height (H) and the distance to rotor (ΔL). Numerical simulations on the static starting torque coefficient were firstly carried out. Based on the method of quadratic rotary orthogonal combination design (QROCD), the starting torque performance effects of the three parameters of WGD on SB-VAWT were researched. Two better structures of WGD optimized were obtained and the flow fields around the rotors with the two kinds of WGD were calculated, the static flow characteristics influence of WGD on the rotor was investigated. Furthermore, the models of the two kinds of WGD were made. Wind tunnel tests were carried out on the static torque characteristics, rotational speed performance from static condition to stable condition and the power characteristics at different tip speed ratios. The performance effects of the WGD on SB-VAWT were analyzed and discussed. This study can provide a new reference for the research of a suitable WGD to improve the performance of SB-VAWT.

2. Basic wind gathering theory of WGD

The wind gathering theory of the truncated-cone-shaped WGD is simple and can be simply explained in Fig. 2. When the rotor is not considered, Fig. 2 can be thought as a cross section diagram of the WGD. Based on the continuity equation of in-compressible tube flow shown in Eq. (1), the average wind velocity at the entrance of the rotor tip ($\overline{U_2}$) can be increased based on the area change of flow tube. When considering the rotor of SB-VAWT, the increasing degree of wind speed flowing into the rotor may be affected in some degree due to the rotor blocking effect, which depends on the structure of rotor and WGD and the relative position of them. Since the torque and power of wind turbine are proportional to the square and cube of the wind speed respectively, both the torque and power performance of the SB-VAWT with WGD will be improved in some degree.

$$A_1\overline{U_1} = A_2\overline{U_2} \tag{1}$$

where, A_1 is cross-sectional area of outside edge of the WGD, A_2 is cross-sectional area of inside edge of the WGD, $\overline{U_1}$ is average speed of the cross-sectional area of outside edge, $\overline{U_2}$ is average speed of the cross-sectional area of inside edge.

3. Model design

Fig. 3 shows the structural diagram and photo of the rotor model of SB-VAWT with the truncated-cone-shaped WGD designed in the study.

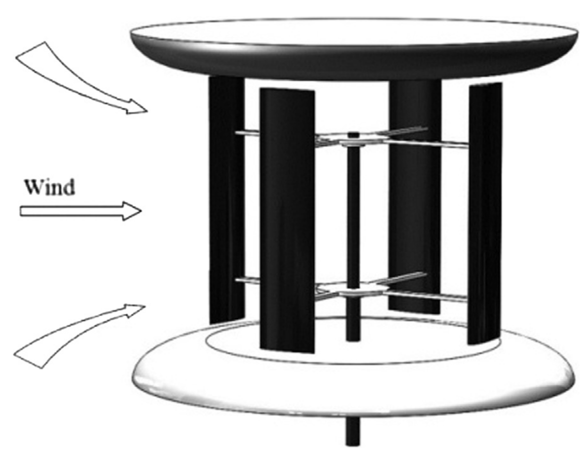

Fig. 1. Concept of WGD set top and bottom of the rotor.