Vertical-Axis Wind Turbine

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Basic equations for estimating the aerodynamic power captured by the Anderson vertical-axis wind turbine (AVAWT) are derived from a solution of Navier–Stokes (N–S) equations for a baroclinic inviscid flow. In a nutshell, the pressure difference across the AVAWT is derived from the Bernoulli’s equation—an upshot of the integration of the Euler’s momentum equation, which is the N–S momentum equation for a baroclinic inviscid flow. The resulting expression for the pressure difference across the AVAWT rotor is plotted as a function of the free-stream speed. Experimentally determined airstream speeds at the AVAWT inlet and outlet, coupled with corresponding free-stream speeds, are used in estimating the aerodynamic power captured. The aerodynamic power of the AVAWT is subsequently used in calculating its aerodynamic power coefficient. The actual power coefficient is calculated from the power generated by the AVAWT at various free-stream speeds and plotted as a function of the latter. Experimental results show that at all free-stream speeds and tip-speed ratios, the aerodynamic power coefficient of the AVAWT is higher than its actual power coefficient. Consequently, the power generated by the AVAWT prototype is lower than the aerodynamic power captured, given the same inflow wind conditions. Besides the foregoing, the main purpose of this experiment is to investigate the technical feasibility of the AVAWT. This proof of concept enables the inventor to commercialize the AVAWT.

Anderson vertical-axis wind turbine   blockage factor   power coefficient

1. Introduction

Albeit vertical-axis wind turbines (VAWT) are not new to subject-matter experts, it is worthwhile shedding some light on them so that readers who are not subject-matter experts can acquire some knowledge about these contrivances. Besides, the VAWT under investigation, named the Anderson VAWT (AVAWT) under the patent number US8790069 [1], is a new contraption that makes an overview of existing VAWTs relevant. The novel VAWT is different from existing ones in the sense that its blades are made of specially rolled sheet metal giving them the desired curvature for proper aerodynamic performance. It is a three-stage device with each stage made up of three specially curved blades, placed 120° from each other. The top stage leads the middle stage by a few degrees, while the same is true for the middle and bottom stages. In order to investigate the aerodynamic feasibility of a curved bladed Darrieus vertical-axis wind turbine (DVAWT) rotor, engineers at the Sandia National Laboratory of the U.S. Department of Energy (USDOE) developed a 5 m-diameter, two-bladed prototype that was mounted on the roof of their laboratory and seen to rotate on windy days. Following the aforementioned rotor was the development of a 17 m-diameter curved two-bladed rotor that was observed to perform nearly as efficiently as a horizontal-axis wind turbine (HAWT) rotor of equal capacity. A 34 m-diameter VAWT of the same type, called the test rig by Sandia, was developed thereafter and incorporated with instruments for condition monitoring and those to record weather conditions that affect its performance. Sandia also used this VAWT to validate various computer models, test airfoil designs and develop various control strategies [2]. Unlike this study that performed a wind tunnel experiment to investigate the performance of a novel VAWT, Sandia performed on-site investigations on a working VAWT.

2. The Performance of a Novel Vertical-Axis Wind Turbine

Typically, VAWTs may have either drag-driven or lift-driven rotors. A Savonius rotor is the most common drag driven rotor. It has been used on water pumps and is inexpensive to manufacture. Savonius machines typically have low power coefficients because they are drag driven. Power coefficients of about 0.30 are typical of Savonius rotors. Additionally, they have a solidity close to unity, such that they are very heavy relative to their power production capacities, and it is also difficult to protect them from high winds [3].

A DVAWT is a lift-driven machine. Lift-driven VAWTs have almost always been used for electrical power generation. Lift-driven VAWTs typically have rotors with straight or curved blades. Some VAWTs with straight-blade rotors have a pitching mechanism, even though most lift-driven VAWTs have fixed blades. Yawing mechanisms are not needed on VAWTs, since they see the wind in any direction. Rotor blades of lift-driven VAWTs are generally untwisted and have constant chords; thus, they are easy to mass-produce. VAWTs are prone to high fatigue damage because the load on each blade varies during each rotation of the rotor. They are difficult to support on separate tall towers, since a large portion of the rotor tends to be close to the ground in a region with low wind speeds. This results in less productivity, compared to a HAWT of the same capacity [3][4].

In 1988, a 100 m tall, 60 m-diameter DVAWT was installed in Canada. The 60 m-diameter VAWT ran for six years with 94% availability [3]. As stated earlier, DVAWTs work on the principle of aerodynamic lift (i.e., the wind pulls the rotor blades along). On the contrary, the traditional Holland type windmill operates on the principle of drag (i.e., the wind pushes a manmade barrier such as a rotor blade) [2]. Typically, DVAWTs have power coefficients between 0.4 and 0.42 [5]. They are not self-starting; some drag ought to be imposed on them for them to be able to be self-starting. Installation of cups or vanes on DVAWTs makes them capable of trapping the wind, thereby causing them to self-start [2][4]. Using the foregoing methods to self-start DVAWTs results in larger blades, and these methods have been abandoned. To encourage the development of the wind energy technology in the U.S., the Federal Government gave incentives such as a tax credit of 1.80 cents/KW-h of wind energy produced. The USDOE set a goal in 2008 to achieve a 20% contribution to grid power by wind energy sources by the year 2030 [2]. This is clear evidence of the fact that there is a niche for wind energy in the U.S. energy market.

VAWTs can be effectively used in urban areas where turbulent and unsteady wind is typical [6][7]. They have inherent superiority over HAWTs in severe wind conditions, because the wind enters their rotors from about any direction without yawing. A discrepancy factor of two typically exists between computational fluid dynamics (CFD) results and results of wind tunnel experiments, since the effects of a finite blade length and spoke drag are not usually considered in CFD analysis. The performance of a VAWT with a steady inflow condition is not a reflection of the actual performance of a VAWT operating in an urban environment - an upshot of the fact that wind fluctuates in an urban environment. The performance of a wind turbine (WT) depends on the cube of the speed of the inflow wind; thus, moderate fluctuations in the wind speed would result in very large fluctuations in power output [6]. The seeming stagnation in improvements on the aerodynamics of HAWTs has spurred interest in the development of large-scale VAWTs. Another factor in favor of VAWTs is the future demand for decentralized and sustainable energy supply in cities and rural communities [8]. They are suitable where HAWTs do not operate efficiently, usually at locations with high wind speeds and turbulent wind flow. VAWTs are quieter than HAWTs, which makes them suitable for use in urban areas [9][10]. Savonius VAWTs can withstand gusts due to their superior stalling behavior and are suitable for use in gusty environments. At a tip-speed ratio of unity, the power coefficient of a Savonius rotor is optimal. Modifications on the blade geometry of Savonius rotors improve their power coefficients. The power coefficient of a Savonius rotor with a 45° angle of twist is 0.3385 compared to 0.30 for rotors with untwisted blades. Two-stage Savonius rotors perform better than their three-stage counterparts [9]. Both three-bladed and two-bladed Savonius rotors exhibit high power coefficients at low tip-speed ratios.

Curved DVAWTs with troposkein shapes are prone to nearly tensile loads and minimal bending moments on their rotor blades. They operate at distinct angles of attack at different azimuth angles and are subjected to cyclic aerodynamic loads that can result in fatigue [10]. Cognizant of the aforementioned setback on the curved DVAWTs and other VAWTs, experimental investigations and numerical simulations to ascertain their suitability for use are imperative. The International Electro-Technical Commission (IEC) guidelines include well established procedures for WT testing. Based on the IEC guidelines, the service life of a WT is 20 years. Breakdowns are frequent with WTs, and such breakdowns stem from manufacturing and design errors due to underestimated fatigue loads or extreme loads. Consideration of turbulent inflow conditions during aerodynamic modeling is of paramount importance. Turbulent characteristics of inflow air may have an impact on fatigue loads experienced by WTs [11].

Blade pitching is more difficult for VAWTs than for HAWTs due to the dependence of the angle of attack of the former on the rotor azimuth angle, resulting in the existence of very few practical pitch control schemes for VAWTs [12]. Unlike some of the existing VAWTs, which may require pitch control to maximize wind energy capture, the VAWT in this study does not require pitch control for wind energy capture optimization.

Extraction of wind momentum by a VAWT occurs more during the upwind pass. Most of the VAWT's power output is produced on the upwind pass, whereas flow momentum is considerably reduced on the downwind pass, hence resulting in a reduced power output [13]. Darrieus-type VAWTs with straight blades are less efficient than those with helically twisted blades [14]].

Various numerical and analytical schemes have been implemented in a bid to investigate performance characteristics of VAWTs. Zanon et al. [15] solved potential flow equations in conjunction with integral boundary layer equations formulated for VAWT rotors, using a semi-inverse iterative algorithm. From their simulations, they inferred that VAWTs can be designed to avoid the occurrence of dynamic stall resulting from blade-vortex interaction in the downward part of rotor rotation during gusts and normal operation, and even at low tip-speed ratios [16]. Scheurich et al. [14] implemented a CFD scheme based on the vortex transport model (VTM). The VTM is based on solving Navier–Stokes (N–S) equations in terms of the vorticity and velocity. The governing momentum equation is expressed in terms of the vorticity and velocity and is the result of finding the curl of the velocity and pressure-based N–S momentum equation. In their work on the steady-state and dynamic simulations of Savonius rotors, Jaohindy et al. [16] found that the best approximations of the static torque coefficient, the dynamic torque coefficient and the power coefficient were obtained using the shear stress transport-k-ω model rather than the k-ε turbulence model. At startup, dynamic torque coefficient curves of a Savonius rotor oscillate around fixed values in polar coordinates [16]. There is a significant difference between simulated and experimental values of the power coefficient of a DVAWT at high tip-speed ratios, even though simulation and experimental power coefficient values follow the same trend as the tip-speed ratio varies [17]. The power coefficient of a Darrieus-type VAWT peaks at tip-speed ratios between 3 and 4 and drops for tip-speed ratios greater than 4 for both CFD simulation and experimental results, with values of the former being slightly higher than those of the latter (see Figure 18 in [18]).

This study uses an experimental approach to investigate the performance of the novel AVAWT [1]. Unlike CFD simulations performed by some of the above cited researchers, which were based on two or three tip-speed ratios, this study investigates performance characteristics of the novel AVAWT over a broad range of tip-speed ratios.

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