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Critical Design Parameters Affecting the Performance of Small Wind Turbine Blades at Low Wind Speeds: A Review

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Abstract

The aerodynamic efficiency of a wind turbine relates to the ability of the rotor to transform kinetic energy in the wind to mechanical energy. Some of the parameters interacting in this process are air density, rotor swept area, blade geometry, airfoil configuration, and the wind velocity. Of these, blade design is a prevailing factor as it dictates the forces acting in the air that produce torque and the forces that extract energy. This paper presents a review of the main design variables influencing the power coefficient and the overall output of horizontal-axis wind turbines. Special attention is paid to the effect of tip speed ratio and blade pitch angle on aerodynamic performance. The literature suggests that the optimal rotor efficiency is reached within the range of tip speed ratio (4-7) and the pitch angle (0^o - 3^o). The effectiveness of the turbine in converting energy is greatly improved by the optimization of these parameters.

Keywords: Refrigerants; Renewable Energy; Windmills; Small Wind Turbines; Environment; BEM Theory; X-Foil; Chord; Twist; Airfoil

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Introduction

Wind energy is a viable alternative to power generation which uses fossil fuel. It is renewed naturally, eco-friendly, and will not produce greenhouse gases during the process and will only need relatively less land use. Increasing the efficiency of wind turbines will increase the amount of electricity produced and decrease the need to use expensive and polluting traditional energy systems. The use of wind in practical manner has many centuries old history and it is also important in the development of man. The renewable energy sources are replenished naturally and can be transformed into practical power with the help of technologies that use solar rays, wind blows, running water, sea waves, natural geothermal energy, and biological processes. Of these alternatives, wind energy conversion systems have experienced a tremendous technological development. Power gathered by the wind is mainly based on the density of the air, the area covered by the rotor, and the wind speed. The design of blades is particularly crucial as it defines the aerodynamic interplay between the rotor and airflow directly affecting the performance of turbines and their energy production.

Different Theory Used in Blade Design

A turbine rotor is constructed of aerodynamic sections of the blade (airfoils) which generate lift following the pressure differences of the surfaces on the upper and bottom. This mechanism of lift generation can be modeled on the basis of actuator disc concepts with the rotor being considered a permeable disc that extracts energy out of the wind stream. In this method, the flow field around is considered in terms of the conservation of linear and angular momentum. Axial and tangential induction factors define the aerodynamic behavior of the rotor, and are directly linked to thrust and power extract. The current analysis uses both the momentum theory and the blade element theory. The momentum theory is a theory that relies on the control volume theory to estimate the overall rotor forces, and blade element theory is a theory that estimates aerodynamic forces at individual blade sections using local geometry and flow conditions. Combining these approaches, the Blade Element Momentum (BEM) theory is developed, which allows forecasting the performance of rotors and dependence on the blade geometry and the amount of power that can be extracted.

Wind Turbine Blade

A wind turbine works by applying aerodynamic lift forces on the turbine blades to turn a shaft. The shaft generates the rotational mechanical energy which is then converted to electrical energy by a generator. According to the relative position of the rotor shaft to the ground, the wind turbine can be classified into two broad categories: (i) Horizontal Axis Wind Turbine (HAWT) and (ii) Vertical Axis Wind Turbine (VAWT). In horizontal axis wind turbine, the rotor shaft is oriented in the direction of the wind, and in a vertical axis wind turbine, the shaft is oriented perpendicular to the wind flow. Both configurations possess different design features, performance benefits and uses.

Review Of Work Carried Out on Different Individual Parameter

Small Wind Turbines under Low Wind Conditions

Low-speed wind turbines are highly influenced by the low Reynolds number aerodynamics, and as a result, laminar separation and low lift generation are generally experienced. Strategies on performance improvement are aimed at maximising the blade number, solidity and tip speed ratio (TSR). A parametric study of blade twist and chord distribution was conducted by M. K. Chaudhary and Roy [1], which showed that at TSR and solidity 3-, 5-, and 7-bladed rotors would give the highest Power Coefficient values of 0.46, 0.50 and 0.48 respectively. R. Singh and A. Ahmed [2] developed a two-bladed rotor in low wind regimes with a specially designed AF300 airfoil, which exhibits better start-up behavior. A micro wind turbine (500 mm diameter) was developed by T. Hirahara et al. [3] and experimentally a power coefficient of about 0.40 maximum (at TSR = 2.7) was obtained. Equally, D. A. Wright and D. H. Wood [4] looked at start-ups of small turbines and noted the significance of the aerodynamic torque at low wind speeds.

Rotor Blade Optimization

The optimization of blade geometry has a great effect on turbine efficiency. Aerodynamic loading and structural performance are dependent on parameters like chord length, twist distribution and airfoil selection. F. Maalawi and M. A. Badr [5] pointed to the importance of optimization of blade number and chord in the cut-in speed of the wind. C. Fuglsang and H. A. Madsen [6] suggested a numerical optimization method to the design of HAWT blades, which suggested a better selection of the airfoils to maximize the lift coefficient. R. Rathore and S. Ahmed [7] optimized a 750 kW HAWT blade by using finite element analysis and P. Pathike et al. [8] showed a significant enhancement in efficiency (27%) of optimized blades at 6 m/s relative to commercial designs (16.5%).

Airfoil Selection and Aerodynamic Performance

Airfoil shape has a direct influence on the lift-to-drag ratio and stalls. H. Ozgener [9] experimentally compared the blade material and configurations and observed the effect of aspect ratio on aerodynamic efficiency. A study by S. Schubel and R. Crossley [10] indicated that increased tip speeds demand less chord widths and accurate aerodynamic profiling. J. F. Lanzafame and M. Messina [11] demonstrated that optimization of blade profile and lift coefficient improves the torque generation and rotor efficiency. The low Reynolds number airfoil such as AF300 was studied and the results showed that it had better ClC lCl and L/DL/DL/D ratios under small turbine operating conditions [2], [12].

Effect of Pitch Angle

The angle of blade pitch has a major influence on power coefficient, and start-up performance. Singh and Ahmed [2] noted that optimized power coefficient values were better at low wind speed ranges with optimized pitch settings. Experimentally an experimental study by Lanzafame and Messina [11] confirmed a mathematical model illustrating amplified power coefficient at low wind velocities (via pitch optimization). The aerodynamic efficiency of turbines is indicated by the power coefficient (CpC, pCp). Multi-objective optimization methods were used by A. Benini and A. Toffolo [13] to maximize the annual energy production and minimize cost. Studies have shown that solidity increases starting torque and could lead to better power coefficient at lower TSR values, but too much solidity can raise drag losses [5], [6].

Conclusion

The literature reviewed provides a very clear picture of the design of small wind turbine blades, with a major number of modern designs being horizontal axis wind turbines (HAWTs) because of their better aerodynamic performance and higher power coefficients than vertical axis designs. The past studies have concentrated on most of the parameters that included the rotor blade number, fixed chord and untwisted blade profiles, optimization of the pitch angle, and the solidity of the blades. A number of studies have shown that the more the blades, the better the aerodynamic performance at low wind speeds. The experimental data indicate that raising the number of blades, three to seven, enhances the power coefficient (Cp) by about 10%. The rotor with three blades had Cp of 0.40 and 0.46 at the 0 and 3 degree pitch, respectively. In the same way, a five-blade rotor achieved Cp values of 0.44 and 0.50 and a seven-blade rotor achieved Cp values of 0.46 and 0.48 at the respective pitch angles. Although much effort has been made on blade number and pitch change, relatively little research has been done on the topic of advanced blade geometry, including changing chord distribution and twist optimization. Thus, the current research aims at enhancing rotor performance, shortening cut-in wind speed and optimizing the blade geometry using chord variable and twisted blades with reasonable design accuracy.

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