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Optimization of power coefficient on a horizontal axis wind turbine using bem theory

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ABSTRACT

Aerodynamic optimization has widely become a issue of considerable interest to determine the geometry of an aerodynamic configuration amidst certain design constraints. Aerodynamic performance is calculated from a prescribed geometric shape, which is often performed in trial and error method. Numerous design methods are available for the aerodynamic design of the rotor. The goal in optimizing is to maximize the aerodynamic efficiency at a single design wind speed. However, single-design point methods do not automatically lead to the optimum design, since they consider only one point in the total operational range. Moreover they do not implicitly involve considerations on loads which require an experienced designer. The aerodynamic optimization of a Horizontal Axis Wind Turbine is a complex method characterized by numerous trade-off decisions aimed at finding the optimum overall performance. However researcher design the wind turbine is an enormous ways and more often decision-making is very difficult. Commercial turbines have been derived from both theoretical and empirical methods, but there is no clear evidence on which of these is optimal. Turbine blades are optimized with the aim to achieve maximum power coefficient for the given blade with solidity, ratio of coefficient of drag to lift, angle of attack and tip speed ratio. In this article, the blade element theory is used to find the optimum value analytically. The effect of power coefficient for different blade angle, tip speed ratio, ratio of coefficient of drag and coefficient of lift and blade solidity is presented and the optimized set value is obtained.

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1. Introduction

Wind is caused due to uneven heating of the land and water by the sun on the earth. This temperature difference induces circulation of air from one region to another. Wind energy conversion system is one with low investment and high yield power generation. The main advantage of electricity generation from wind energy is the absence of harmful emissions. Thirst on energy, the missile price increase of fossil fuels, hazardous impact on environment, uncertain supply of fuel have made the nation to rely on renewable energy sources. Variation in wind velocity round the clock must be extracted with the available wind electric converter and hence wind electric generators must be capable to operate under varying speed and this led to the development of variable-speed wind turbines nowadays. The power produced by a wind electric generator at a specific site depends upon the mean wind speed at the site, hub height, the speed characteristics of the wind turbine cut-in speed, rated speed, and furling wind speeds.

2. Performance and design aspects of horizontal axis wind turbine

Designing wind turbines to achieve satisfactory levels of performance and durability should have deep knowledge in the factors affecting wind power, aerodynamic forces acting in the turbine. Energy conservation, pollution prevention, resource efficiency, systems integration and life cycle costing are very important terms for sustainable construction. Designing wind turbine principles includes: (i) minimizing non-renewable resource consumption, (ii) enhancing the natural environment and (iii) eliminating or minimizing the use of toxins, thus combining energy efficiency with the impact of materials on occupants [1]. Therefore, possible use of wind energy must be evaluated in terms of its impact on the environment.

2.1. Power available in the wind

The three factors that determine the output from a wind energy converter are wind speed, cross-section of wind swept by rotor, and overall conversion efficiency of the rotor, transmission system and generator. Energy available in wind is equal to the kinetic energy of wind. If ρ is the density of the air in kg/m^3, A is the swept area in m^2, and V_m is the mean velocity of wind in m/s, then total wind power available, P_a,

$$P_a = \frac{m_w V_m^2}{2} Watts = \frac{\rho A V_m^3}{2} Watts$$

The above equation shows that the wind power varies as the cube of the wind velocity. However density varies with pressure, temperature and relative humidity. Unfortunately, the total wind energy cannot be recovered in a wind turbine because the output wind velocity cannot be reduced to zero, otherwise there would be no flow through the turbine [2]. Let V_i be the inlet wind velocity and V_o be the outlet wind velocity, $m_w = \rho \cdot A \cdot V_{ave}$ be the mass flow rate with average velocity $(V_i + V_o)/2$ and the power recovered from the wind (P_{out}) is equal to the rate of change in the kinetic energy.

$$\begin{aligned} P_{out} &= m_w (V_i^2 - V_o^2)/2 \\ &= \rho A V_{ave} (V_i^2 - V_o^2)/2 \\ &= (\rho A)(V_i + V_o)/2 (V_i^2 - V_o^2)/2 \\ &= (\rho A/4)(V_i^3 + V_i^2 V_o - V_i V_o^2 - V_o^3)/V_i^3 \end{aligned}$$

$$Take\ x = V_o / V_i$$

$$P_{out} = (1 + x - x^2 - x^3) P_a / 2 \tag{1}$$

Differentiating (1) with respect to x and equating to zero, we get the optimum value of x for maximum power output.

$$d(P_{out})/dx = 0 \Rightarrow 1 - 2x - 3 \times^2 = 0$$

Solving the quadratic equation, the value of $x = 1/3$.
Substituting the value of x in (1), we get

$$P_{out\ \mathrm{max.}} = 0.593 P_a$$

Thus the maximum that can be drawn from the wind system is 59.3% of the total wind power available, which is called Betz limit in aerodynamics.

The power coefficient C_p is defined as

$$C_p = \frac{P_s}{(1/2).\rho.\pi.R^2.U_o^3} \tag{2}$$

where, P_s is the shaft power output in Watts, U_o is the upstream undisturbed wind speed in m/s. The power performance of a wind turbine can be expressed using fixed angular velocity. This parameter is defined as

$$C_M = \frac{C_p}{\lambda} \tag{3}$$