

Aerodynamic Performance Modeling and Optimization of Small Scale Wind Turbine Rotors

Athwel Gamarallage Thisitha Sugathapala
Senior Lecturer, Department of Mechanical Engineering
University of Moratuwa
Moratuwa 10230, Sri Lanka

Abstract—This paper presents aerodynamic performance modeling and optimization of small scale wind turbine rotors for off-grid electricity generation applications targeting local manufacturing through simplification of blade geometry with constant chord and linear twist. The classical momentum theory and blade element theory are used to derive the governing equations, which are solved through an iterative procedure and search method for optimization. The results show that the aerodynamic performances of the simplified rotor designs are quite satisfactory, thus enhancing potential for local manufacture.

Keywords—wind energy; rotor aerodynamics; power coefficient

I. INTRODUCTION

Development of renewable energy (RE) resources is considered to be one of the key interventions for the mitigation of energy and environment crises arisen from excessive usage of fossil fuels for energy generations. Wind energy resources are abundantly available in Sri Lanka, and the government has resolved to implement aggressive development plan to realize its target of 100% RE scenario by 2035, while improving the energy access to the entire community [1]. The emphasis is on popularizing decentralized RE energy projects that could contribute to local socio-economic development. Thus, development of small-scale wind energy conversion systems (WECSs) for rural-electrification with local manufacturing perspectives is an important step. However, the design and manufacture of the rotor, which is one of the key sub-systems in WECSs, need sophisticated tools and skills. Therefore, the overall objective of this research work is to establish a basic mathematical model for the aerodynamics performance characteristics of a wind turbine rotor and thereby develop an optimized rotor with simplified blade geometry for local manufacture.

II. AERODYNAMIC PERFORMANCE OF WIND TURBINE ROTORS

A. Governing Parameters

The function of a wind turbine rotor is to convert optimally the kinetic energy in the moving air into mechanical energy to drive the electric generator. The rotor slows down the moving air while converting kinetic energy to pressure energy, which forces the rotor blades to generate the mechanical energy. This process is basically governed by fluid dynamics principles together with characteristics of flow around airfoil sections

of the blades [2]. Thus, the governing variables of the rotor flow dynamics include the input parameters such as fluid properties (primarily, density ρ and dynamic viscosity μ), flow characteristics (primarily, air velocity U), and geometrical properties (such as rotor diameter D , number of blades B , airfoil shape and size variations of the blades) and output parameters such as rotor power P , rotational speed ω and torque T . The system performance of a wind energy conversion facility is also determined by the performance characteristics of other sub-systems such as the mechanical transmission systems, electric generator, control systems, and electric load characteristics. The scope of this research work is limited only to the modeling of the aerodynamic performance characteristics of small-scale rotors for electricity generation applications.

B. Functional Relationships

The basic relationships between the governing parameters could be derived through dimensional analysis technique, in which the overall performance parameters of the rotor are expressed in non-dimensional forms as the Power Coefficient C_p and Torque Coefficient C_T , defined by [3],

$$C_p = \frac{P}{P_{\infty}} = \frac{P}{\frac{1}{2}\rho U^3(\pi R^2)}, \quad (1)$$

$$C_T = \frac{T}{\frac{1}{2}\rho U^3(\pi R^2)} = C_p \left(\frac{U}{R\omega} \right) = \frac{C_p}{\lambda_t}, \quad (2)$$

where $R = D/2$ is the rotor radius and $\lambda_t = R\omega/U$ is referred to as the tip speed ratio. In general, both C_p and C_T are functions of several non-dimensional independent parameters such as Reynolds number $Re = \rho U D/\mu$, λ_t , B , rotor solidity σ and aerodynamic performance parameters of the blade profile such as lift coefficient C_l and drag coefficient C_d . In a rotor design, these parameters are selected for optimum performance for a given application. Then the rotor performances, given by C_p and C_T , become functions of Re and λ_t , among which Re representing effects of friction on the aerodynamics loads has minor effects. As such, the overall performance characteristics

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Table of Contents Aerodynamic Design Optimization Of Wind Turbine Rotors

1. Understanding the eBook Aerodynamic Design Optimization Of Wind Turbine Rotors
 - The Rise of Digital Reading Aerodynamic Design Optimization Of Wind Turbine Rotors
 - Advantages of eBooks Over Traditional Books
2. Identifying Aerodynamic Design Optimization Of Wind Turbine Rotors
 - Exploring Different Genres
 - Considering Fiction vs. Non-Fiction
 - Determining Your Reading Goals
3. Choosing the Right eBook Platform
 - Popular eBook Platforms
 - Features to Look for in an Aerodynamic Design Optimization Of Wind Turbine Rotors
 - User-Friendly Interface
4. Exploring eBook Recommendations from Aerodynamic Design Optimization Of Wind Turbine Rotors
 - Personalized Recommendations
 - Aerodynamic Design Optimization Of Wind Turbine Rotors User Reviews and Ratings
 - Aerodynamic Design Optimization Of Wind Turbine Rotors and Bestseller Lists

5. Accessing Aerodynamic Design Optimization Of Wind Turbine Rotors Free and Paid eBooks
 - Aerodynamic Design Optimization Of Wind Turbine Rotors Public Domain eBooks
 - Aerodynamic Design Optimization Of Wind Turbine Rotors eBook Subscription Services
 - Aerodynamic Design Optimization Of Wind Turbine Rotors Budget-Friendly Options
6. Navigating Aerodynamic Design Optimization Of Wind Turbine Rotors eBook Formats
 - ePub, PDF, MOBI, and More
 - Aerodynamic Design Optimization Of Wind Turbine Rotors Compatibility with Devices
 - Aerodynamic Design Optimization Of Wind Turbine Rotors Enhanced eBook Features
7. Enhancing Your Reading Experience
 - Adjustable Fonts and Text Sizes of Aerodynamic Design Optimization Of Wind Turbine Rotors
 - Highlighting and Note-Taking Aerodynamic Design Optimization Of Wind Turbine Rotors
 - Interactive Elements Aerodynamic Design Optimization Of Wind Turbine Rotors
8. Staying Engaged with Aerodynamic Design Optimization Of Wind Turbine Rotors
 - Joining Online Reading Communities
 - Participating in Virtual Book Clubs
 - Following Authors and Publishers Aerodynamic Design Optimization Of Wind Turbine Rotors
9. Balancing eBooks and Physical Books Aerodynamic Design Optimization Of Wind Turbine Rotors
 - Benefits of a Digital Library
 - Creating a Diverse Reading Collection Aerodynamic Design Optimization Of Wind Turbine Rotors
10. Overcoming Reading Challenges
 - Dealing with Digital Eye Strain
 - Minimizing Distractions
 - Managing Screen Time
11. Cultivating a Reading Routine Aerodynamic Design Optimization Of Wind Turbine Rotors
 - Setting Reading Goals Aerodynamic Design Optimization Of Wind Turbine Rotors
 - Carving Out Dedicated Reading Time
12. Sourcing Reliable Information of Aerodynamic Design Optimization Of Wind Turbine Rotors
 - Fact-Checking eBook Content of Aerodynamic Design Optimization Of Wind Turbine Rotors
 - Distinguishing Credible Sources
13. Promoting Lifelong Learning

- Utilizing eBooks for Skill Development
 - Exploring Educational eBooks
14. Embracing eBook Trends
- Integration of Multimedia Elements
 - Interactive and Gamified eBooks

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