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Optimized Blade Design Through Numerical Analysis for Enhanced Wind Turbine Performance

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Abstract

In recent years, the urgency for transitioning to renewable energy sources (RES) has intensified, as approximately 75% of global greenhouse gas emissions result from fossil fuel use. Among RES, wind energy stands out for its low cost, environmental benefits and ongoing technological improvements. Although recent studies have identified several locations in the Republic of North Macedonia (RNM) with high wind energy potential, the country's wind resources remain largely underutilized, and research on turbine design optimized to local conditions is lacking. Given the fluctuating nature of wind energy, increasing the efficiency and reliability of wind power systems has become a key focus of the wind turbine industry through innovative approaches in their design and implementation. In response to this gap, the present study investigates blade design optimization for a specific high-potential location in RNM, addressing the absence of studies that adapt aerodynamic design to the country's wind conditions. The study aims to improve the performance of a horizontal axis wind turbine (HAWT), by applying an optimization methodology based on mathematical modelling and simulation techniques. The study is conducted for a predetermined wind speed range, which is chosen according to the conditions at the specific location. For a desired installed power and the basic geometric and operating parameters of a HAWT, several suitable aerodynamic blade profiles were investigated. After an evaluation of the airfoils, a selection was conducted on the basis of their aerodynamic performance. The selected airfoil was used for the HAWT rotor blades composition. Three models of rotor blades were developed based on different chord length and twist angle distributions. A numerical model was developed using a software tool to simulate the flow through the blades with different geometries to predict their impact on the HAWT performance at various operating conditions. These simulations yielded the output parameters that characterize the wind turbine performance. The simulation results provided valuable insights into how blade geometry affects overall turbine behaviour and efficiency. The outcomes confirm that the proposed optimization methodology can support the selection of site-specific blade designs, improving wind turbine performance and revealing new opportunities for efficient and localized wind energy production in RNM.