Wind Turbines Operating under Hazard Environmental Conditions

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Renewable energy use has accelerated due to global warming, depleting fossil fuel reserves, and stricter environmental regulations. Among renewable options, solar and wind energy have shown economic viability and global growth. Horizontal axis wind turbines offer promising solutions for sustainable energy demand. Since wind turbines operate in an open environment, their efficiency depends on environmental conditions. Hazard environmental conditions, such as icing, rainfall, hailstorms, dust or sand, insects' collisions, increased humidity, and sea spray, result in degraded aerodynamic characteristics.

Keywords: aerodynamic characteristics ; wind turbine ; icing ; rainfall ; hailstorm ; dust ; sand ; insects ; humidity ; sea spray

1. Introduction

Over the past decade, the utilization of renewable energy sources (RES) has witnessed a significant acceleration in response to the escalating threats posed by global warming, the reduction in fossil fuel reservoirs, and the implementation of stricter environmental regulations in the global energy market and society [1]. Among all the available renewable energy options, solar energy and wind energy have emerged as the most economically viable sources, experiencing rapid growth on a global scale [2]. **Figure 1** illustrates the global distribution of operational and under construction wind farms with capacities of 10 MW or more.

After experiencing a consecutive decline over the past two years, the capacity additions for onshore wind energy are projected to witness a remarkable recovery in 2023, with an anticipated increase of 70% to reach a historic milestone of 107 GW [3]. This resurgence can primarily be attributed to the successful completion of delayed projects in China that were affected by the COVID-19 restrictions imposed last year. Furthermore, accelerated expansion is expected across Europe and the USA, as the challenges faced in the supply chain have caused project commissioning to be postponed from 2022 to 2023. Conversely, the development of offshore wind energy is not projected to match the unprecedented expansion achieved two years ago, largely due to the limited number of projects currently under construction outside of China.

Two main types of wind turbines exist, categorized based on their rotor structure and position in airflow: horizontal axis wind turbines (HAWTs) and vertical axis wind turbines (VAWTs). HAWTs have gained significant popularity in the commercial electricity generation sector, owing to a considerable amount of time and effort having been invested in their research and development, due to their higher efficiency.

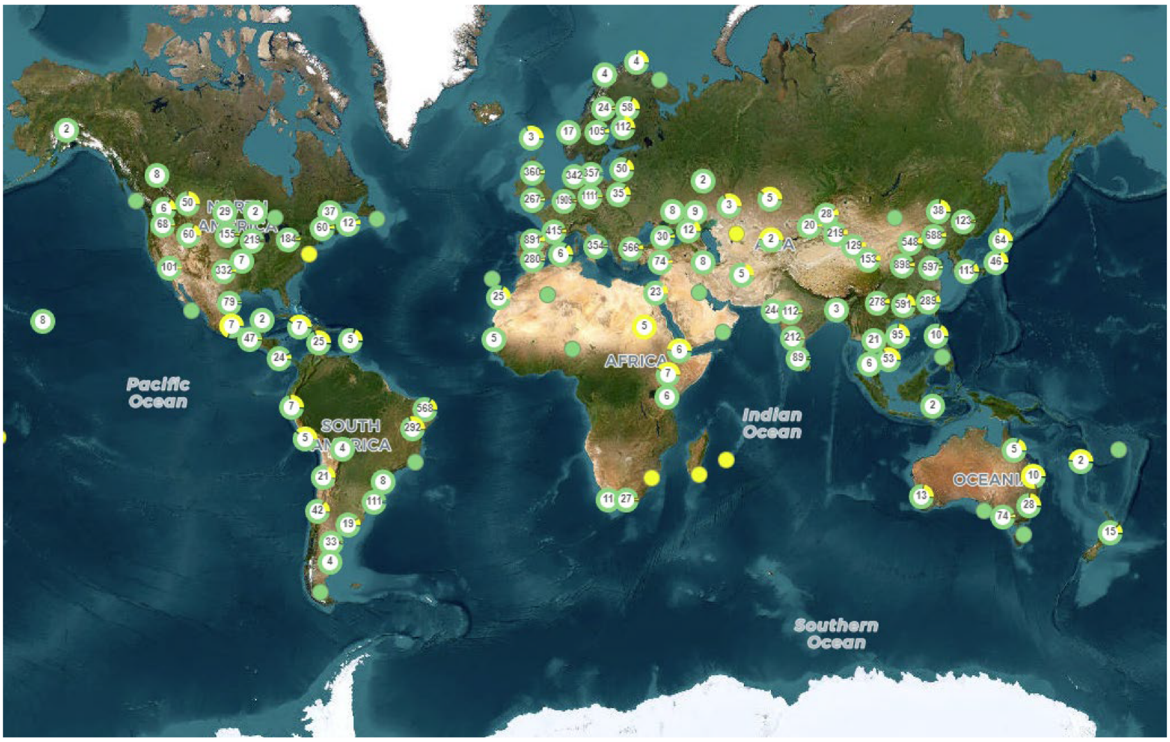

Figure 1. Worldwide map showing the operating (green) and under construction (yellow) wind farms with capacities equal to or exceeding 10 MW [4].

The efficiency of a HAWT is influenced by numerous variables, including the wind speed during operation, the length of the blades, the height of the tower, the design of the casing, and the environmental conditions in the vicinity, including weather conditions, as well as collisions with birds and insects [5].

The aerodynamics of the blade significantly impacts the performance of a HAWT. Additionally, collisions with birds and insects can disrupt the blade's aerodynamic profile, resulting in increased aerodynamic drag and a subsequent decrease in power generation of up to 50% [6][7][8]. Moreover, the accumulation of ice on the surface further impacts the HAWT's performance, leading to a potential decrease in power generation ranging from 20% to 50% [6]. Under normal circumstances, the performance of a HAWT is closely linked to the wind speed profile at a specific site. Any variations in wind speed profiles have a substantial impact on turbine performance.

Achieving accurate calculations of HAWT power curves is crucial for power performance testing and annual energy production (AEP) assessments. The presence of icing causes a decrease in the AEP by up to 17% and leads to a reduction in the power coefficient within the range of 20–50% [9]. Rainfall has the potential to induce erosion on the surfaces of HAWT blades, leading to an increase in surface roughness, which eventually increases the aerodynamic drag of the blades [10][11][12][13][14][15]. Consequently, this leads to a decline in performance and a subsequent loss of energy [10][16]. It is worth noting that erosion on HAWT blades can result in AEP losses of up to 25% [17][18][19][20]. Moreover, the accumulation of dirt and insects on the blade surface can result in roughness, leading to a potential decrease of up to 50% in power output [6][21][22]. The effects of increased surface roughness, resulting from factors such as sand or insect impacts, as well as erosion caused by rain, on the power output of HAWTs were examined in [23].

2. Aerodynamic Performance of Wind Turbines

The blades of the wind turbine harness the kinetic energy of the incoming wind and convert it into mechanical energy stored in the shaft. The shaft is then linked to an electrical generator, which produces electricity. The power output of a wind turbine is determined by the speed of the incoming wind, the size of the turbine, and the area it sweeps. The maximum amount of kinetic energy extractable from the wind is approximately 59.3% of the total available wind power, according to the Betz limit [24]. The power generated by a wind turbine (P) is in direct proportion to the density of the air (ρ), the rotor sweep area (A), the cube of the wind velocity (u), and the aerodynamic coefficient (C_p) as shown by Equation (1) [25].

$$P = \frac{1}{2}\rho A u^3 C_p \tag{1}$$

The maximum aerodynamic coefficient ($Cpmax$) for HAWTs can be calculated by the empirical Equation (2), proposed by Wilson et al. [26]:

$$c_{p_{max}} = \left(\frac{16}{27}\right)\lambda\left[\lambda + \frac{1.32 + \left(\frac{\lambda-8}{20}\right)^2}{B^{2/3}}\right]^{-1} - \frac{0.57 \cdot \lambda^2}{\frac{c_L}{c_D} \cdot \left(\lambda + \frac{1}{2B}\right)} \tag{2}$$

where λ is the tip speed ratio (TSR), ranging from 4 to 20, B is the number of blades, and cL and cD are the aerodynamic coefficients of lift and drag, respectively. It is apparent that the generated power of HAWTs depends on the airfoils, from which the blades are constructed. Thus, any changes in the flow field could lead to changes in the aerodynamic characteristics of the airfoils, and finally impact the power production of HAWTs.

3. Aerodynamic Characteristics of Wind Turbines under Hazard Environmental Conditions

The aerodynamic characteristics of airfoils and wind turbine blades when subjected to adverse environmental conditions necessitates an understanding of how these conditions influence airfoil performance and behavior. Such environmental hazards, such as icing, rainfall, and hailstorms, among others, present specific difficulties that noticeably influence the fundamental principles of airfoil and wind turbine blade aerodynamics.

Icing occurs when supercooled water droplets solidify on the surface of the blade, resulting in an augmented load and structural perturbations that can significantly impair the aerodynamic characteristics of the airfoil. The presence of ice on the surface causes more turbulence in the airflow, leading to increased drag. As a result, the lift generated by the blade decreases, reducing its ability to produce power.

The impact of raindrops on the airfoil surface precipitates an increase in drag and consequent influences on the lift-to-drag ratio, resulting in an overall reduction in operational efficiency and power generation. Moreover, the prolonged interaction of raindrops with the blade’s surface can cause erosion, altering the aerodynamic profile and further impinging on the blade’s performance.

Hailstorms can cause significant harm as well. When hailstones impact the wind turbine blades, they can cause physical damage to them. This damage includes cracks, dents, and changes in shape, which disrupt the normal airflow, leading to a decrease in performance. The occurrence of hailstorms raises concerns about the safety of both the wind turbine and its surroundings. To address these concerns, protective measures need to be taken, and strong blade design practices should be implemented.

When dust and sand are carried by the wind, they can potentially abrade the blade surface, inducing alterations in surface smoothness and shape. Furthermore, the accumulation of particles can disturb the airflow over the blade surface, increasing drag and decreasing lift as a result.

Other hazard conditions that degrade the aerodynamic characteristics of HAWTs are insects, humidity, and sea spray. Accumulated insects on blade surfaces block the airflow, causing an increase in drag. Elevated humidity levels influence air density, thus affecting the aerodynamic characteristics of the airfoil. The salty composition of sea spray causes corrosion and material deterioration on blade surfaces, with consequent effects on aerodynamic performance.

To comprehensively examine the various aspects of the aerodynamic characteristics of wind turbines in hazardous environmental conditions, the literature reviewed has been organized into distinct categories. This classification is intended to present readers with a well-structured framework that facilitates their comprehension of the numerous challenges and factors associated with this field. Firstly, the impact of icing on wind turbines’ aerodynamic characteristics is thoroughly examined. Then, rainfall, another environmental factor significantly affecting the aerodynamic characteristic of wind turbines, is explored. Following this, hailstorms, known for presenting unique challenges to wind turbines’ aerodynamic characteristics and causing damage and performance degradation, are presented. Subsequently, dust and sand are discussed, which are often ignored even though they significantly influence the wind turbines’ performance and lifespan. In addition to the previously mentioned categories, additional hazard conditions are addressed, including the effects of insects, humidity, and sea spray, offering a comprehensive perspective on the broader spectrum of environmental challenges.

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