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Wind energy and electromechanical conversion: operating principles of wind turbines

Energia eólica e conversão eletromecânica: princípios de funcionamento dos aerogeradores
Energía eólica y conversión electromecánica: principios de funcionamiento de los aerogeneradores

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Abstract:
The transition to a low-carbon energy mix has driven the expansion of wind energy worldwide. This article presents a qualitative literature review aimed at analyzing the operating principles of wind turbines, highlighting the processes that convert the kinetic energy of wind into electrical energy. The methodology is based on an integrative literature review covering classic works in energy engineering and recent publications on generation technologies. The results indicate that system efficiency depends on the harmonious integration of blade aerodynamics, mechanical transmission components, and the electrical generator, while respecting the physical limits of energy extraction. It is concluded that mastery of these principles is essential for optimizing wind projects and supporting innovations such as direct-drive turbines and offshore systems, which ensure greater operational reliability and profitability.

Keywords:
Wind energy. Wind turbines. Electromechanical conversion. Betz limit. Renewable generation.

Resumo:
A transição para uma matriz energética de baixo carbono tem impulsionado a expansão da energia eólica globalmente. O presente artigo apresenta uma revisão bibliográfica qualitativa com o objetivo de analisar os princípios de funcionamento dos aerogeradores, destacando os processos de conversão da energia cinética dos ventos em energia elétrica. A metodologia fundamenta-se em uma revisão integrativa da literatura, abordando as obras clássicas de engenharia de energia e publicações recentes sobre tecnologias de geração. Os resultados indicam que a eficiência do sistema depende da integração harmoniosa entre a aerodinâmica das pás, os componentes mecânicos de transmissão e o gerador elétrico, respeitando os limites físicos de extração de energia. Conclui-se que o domínio desses princípios é essencial para a otimização de projetos eólicos, suportando inovações como turbinas direct drive e sistemas offshore, que garantem maior confiabilidade operacional e rentabilidade.

Palavras-chave:
Energia eólica. Aerogeradores. Conversão eletromecânica. Limite de Betz. Geração renovável.

Resumen:
La transición hacia una matriz energética baja en carbono ha impulsado la expansión de la energía eólica a nivel mundial. Este artículo presenta una revisión bibliográfica cualitativa cuyo objetivo es analizar los principios de funcionamiento de los aerogeneradores, destacando los procesos de conversión de la energía cinética del viento en energía eléctrica. La metodología se fundamenta en una revisión integradora de la literatura que abarca obras clásicas de ingeniería energética y publicaciones recientes sobre tecnologías de generación. Los resultados indican que la eficiencia del sistema depende de la integración armoniosa entre la aerodinámica de las palas, los componentes mecánicos de transmisión y el generador eléctrico, respetando los límites físicos de extracción de energía. Se concluye que el dominio de estos principios es esencial para optimizar los proyectos eólicos y respaldar innovaciones como las turbinas de

accionamiento directo y los sistemas marinos, que garantizan mayor confiabilidad operativa y rentabilidad.

Palabras clave:
Energía eólica. Aerogeneradores. Conversión electromecánica. Límite de Betz. Generación renovable.

1. Introduction

Global warming and the urgent need to decarbonize economies have positioned wind energy as one of the central pillars of the worldwide energy transition. Unlike fossil sources, wind generation harnesses an inexhaustible and clean resource, although it presents inherent challenges because of its intermittent and stochastic nature (TOLMASQUIM, 2016). In this context, the wind turbine is the leading technology: it is not merely a mechanical structure, but a complex energy-conversion system that integrates aerodynamics, mechanics, and electromagnetism (BURTON et al., 2011). This study aims to analyze the fundamental operating principles of modern horizontal-axis wind turbines, detailing the subsystems that enable wind capture and its transformation into electricity ready to be fed into the power grid.

2. Theoretical framework

2.1. Kinetic energy conversion and the Betz limit

The fundamental principle of a wind turbine is the extraction of kinetic energy from moving air masses. When wind reaches the rotor blades, the pressure difference produced by the airfoil geometry (lift force) creates torque that rotates the shaft (MANWELL; MCGOWAN; ROGERS, 2010). Classical literature establishes a strict physical limit for this conversion. In 1919, physicist Albert Betz demonstrated that no wind turbine can extract more than 59.3% of the kinetic energy of the wind crossing the rotor swept area. This theoretical ceiling, known as the Betz limit, is the main benchmark for aerodynamic efficiency and guides the design of modern blades toward power coefficients (Cp) close to 50% under real operating conditions (BURTON et al., 2011).

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2.2. Main electromechanical subsystems

The effective conversion of rotational mechanical energy into electrical energy occurs inside the nacelle, the compartment located at the top of the tower. According to Pinto (2013), the traditional system consists of:

- Rotor and low-speed shaft: capture the wind and rotate at relatively low speeds (usually between 10 and 20 rpm).
- Gearbox: coupled to the rotor shaft, it increases rotational speed to the levels required by the generator (often above 1,500 rpm).
- Electrical generator: converts the mechanical energy received from the high-speed shaft into electrical energy through electromagnetic induction.

3. Materials and method

This study is characterized as qualitative research developed through an integrative literature review. The method enabled the synthesis of multiple academic studies to provide a clear understanding of the electromechanical operation of wind turbines. Data were collected from scientific databases and virtual university libraries, encompassing reference books on renewable-energy engineering and articles published between 2010 and 2024. The analysis followed the structural content-analysis technique, categorizing the findings according to aerodynamic principles and the configuration of internal components.

4. Results and discussion

The literature analysis reveals that wind-turbine operation is not merely a matter of size, but of refined electromechanical synchrony. Historically, the gearbox has been the industry standard for matching rotor speed to generator speed. However, the results show that this component is the system's Achilles' heel, accounting for most mechanical failures and maintenance costs (MANWELL; MCGOWAN; ROGERS, 2010). In response to this technological bottleneck, current literature points to the growing adoption of direct-drive wind turbines. In these systems, the gearbox is eliminated and replaced by multipole permanent-magnet synchronous generators that operate efficiently at the same low rotational speeds as the rotor (TOLMASQUIM, 2016). This mechanical simplification was found to increase machine

availability and reduce corrective shutdowns, making it a crucial strategy, especially in offshore environments where maintenance is complex and costly.

5. Final considerations

The study achieved its objective by demonstrating that wind-turbine operating principles rest on the precise interaction between aerodynamics constrained by the Betz limit and the efficiency of electromechanical subsystems. It is concluded that the evolution of these machines has shifted from focusing only on wind capture to prioritizing reliability and a lower levelized cost of energy (LCOE). As a contribution, this article systematized the operational components of turbines and highlighted the transition to gearbox-free systems. Future studies should investigate the effects of fatigue in composite materials used in modern giant blades and the role of pitch and yaw control systems in maximizing energy generation under extreme weather conditions.

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