

Design and maintenance analysis of wind turbine amplifier gearboxes systems exposed to lightning discharges

Análisis de diseño y mantenimientos de sistemas de cajas de engranes amplificadoras de turbinas de aerogeneradores expuestas a descargas por rayo

Berra-Ceballos, Raúl* ^a, Cruz-Gómez, Marco Antonio ^b, Mejía-Pérez, José Alfredo ^c and Castillo-Pensado, Juan Luis ^d

^a  Benemérita Universidad Autónoma de Puebla •  NKP-4234-2025 •  0009-0005-6920-2430 •  2131975

^b  Benemérita Universidad Autónoma de Puebla, •  S-3098-2018 •  0000-0003-1091-8133 •  349626

^c  Benemérita Universidad Autónoma de Puebla •  G-3354-2019 •  0000-0002-4090-8828 •  473808

^d  Benemérita Universidad Autónoma de Puebla •  NOF-1935-2025 •  0000-0002-1172-4843 •  670346

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* ✉ [\[raul.berrac@alumno.buap.mx\]](mailto:raul.berrac@alumno.buap.mx)



Abstract

The global demand for electrical energy from alternative sources has positioned wind power as the most feasible option. The aim of this research was to analyze the design and maintenance of wind turbine gearbox systems exposed to lightning strikes. On the other hand, state-of-the-art gearboxes have an average replacement frequency of 0.4 times the lifespan of the wind turbine. However, those lacking these technologies will experience longer downtimes, impacting their efficiency and profitability. A mixed-mechanism analysis was performed to evaluate gearbox design and maintenance parameters, identifying critical factors such as intermittent torque and lightning strikes. An analysis of existing gearbox design methods prompted the proposal of an alternative method that meets the goals of sustainable development and modernization. The optimization of this technology will be the future work focus.

Resumen

El requerimiento global de energía eléctrica de fuentes alternativas, ha posicionado la generación eólica como la de mayor factibilidad. El objetivo de esta investigación fue analizar el diseño y mantenimiento de sistemas de cajas de engranes de aerogeneradores expuestas a descargas por rayo. Por otro lado, las cajas de engranes de última tecnología tienen frecuencia de sustitución promedio 0.4 de la vida útil del aerogenerador. Sin embargo, los que no cuentan con estas tecnologías experimentarían mayores tiempos muertos impactando su eficiencia y rentabilidad. Un análisis mixto fue realizado en la evaluación de parámetros de diseño y mantenimientos a cajas de engranes, identificando factores críticos; par torsor intermitente y descargas por rayo. Un análisis de métodos existentes de diseño de cajas de engranes fue el detonante para proponer un método alternativo que cumpla con los objetivos del desarrollo sustentable y modernidad. La optimización de esta tecnología será motivo de trabajos futuros.

Design and maintenance analysis of wind turbine amplifier gearboxes systems exposed to lightning discharges.

Objectives	Methodology	Contribution
It evaluated how atmospheric discharges affect the design, reliability and maintenance of gearboxes in wind turbines.	A modeling of the gearbox system was carried out considering loads induced by lightning discharges. Analysis of failures reported in operation.	Optimize maintenance strategies to increase gearbox life and reliability.

Gearboxes in wind turbines, Lightning discharges in gearboxes in wind farms, Autonomous balancing and leveling system.

Area: Promotion of frontier research and basic science in all fields of knowledge

Análisis de diseño y mantenimientos de sistemas de cajas de engranes amplificadoras de turbinas de aerogeneradores expuestas a descargas por rayo.

Objetivos	Metodología	Contribución
Se evaluó cómo las descargas atmosféricas afectan el diseño, la confiabilidad y el mantenimiento de las cajas de engranajes en aerogeneradores.	Se realizó un modelado del sistema de caja de engranes considerando cargas inducidas por descargas de rayo. Análisis de fallas reportadas en operación.	Optimizar estrategias de mantenimiento para aumentar la vida útil y confiabilidad de la caja de engranes.

Cajas de engranes en aerogeneradores, descargas de rayo en cajas de engranes en parques eólicos, sistema autónomo de equilibrio y nivelación

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Peer review under the responsibility of the Scientific Committee MARVID®- in the contribution to the scientific, technological and innovation Peer Review Process through the training of Human Resources for the continuity in the Critical Analysis of International Research.



Introduction

Wind energy is expanding the global electric power generation industry with greater efficiency within the area of sustainable development and zero emissions. To achieve these goals, turbine size continues to increase in all dimensions, capacities, and control through artificial intelligence. This predicts exponential growth for future generations of wind farms with technological improvements in all their components. Banihabib, R., & Assadi, M. [2023].

In recent decades, there has been a major shift in wind turbine technology, leading to the variable-speed wind turbine with a multi-stage gearbox. This type of turbine features a gearbox between the low-speed rotor and a higher-speed electrical generator [usually a doubly fed induction generator]. The purpose of the gearbox is to increase the rotor's rotational speed before powering the generator. In a wind turbine, the gearbox increases the blade rotational speed by 15 to 20 revolutions per minute [RPM] to reach the speed required by the generator.

Wind turbines without gearboxes are called variable-speed direct-drive wind turbines. The synchronous generator is powered directly by the rotor. There are two types of generators for direct-drive wind turbines: permanent magnet generators and electrically excited synchronous generators.

Wind turbines, both onshore and offshore, are exposed to different environments and phenomena that determine the types of failures in wind turbines. In the case study of gearbox systems, the main phenomena related to failure are wear and lightning strikes, which are decisive factors in the wind turbine's lifespan. Alves Ribeiro, J., et al. [2025], Arias Velásquez, R. M. [2024], Farrando, M., et al. [2024] and Verma, P., & Kumar, N. [2021].

The annual lightning strike rate, according to some real-time storm tracking sites, reports an average of 0.6 to 1 cloud-to-ground lightning strike per turbine per year. However, multi-megawatt turbines in exposed hilltop or offshore locations experience around 10 direct lightning strikes per year. This generates a high frequency of lightning strikes on wind turbines, where the rotational axis and its components are part of the discharge channel to the ground system.

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The gears of a wind turbine amplifier box exposed to a lightning strike experience an intense, ultra-rapid burst of energy. The combination of heat, pressure, and electromagnetic fields from the arc concentrates the damage in tiny points, which can damage the entire gear train. Electrical arcs can exceed 20,000 kA. They develop melt craters, brittle cast layers, and heat-affected zones. The rapid expansion of the plasma generates shock fronts, and the metal peels off in microflakes around the pit. Gears exposed to plasma may suffer from: Surface erosion, sputtering, ion bombardment, sharp tooth edges, high energy neutrals and radicals, return currents, passing through lubricated spaces, lubricant degradation, attack of oils by plasma reactive [O, OH, F, Cl], vacuum or low pressure plasmas, thermal and mechanical stress, localized heating of discharges, induce thermal cycles, microcracks, increased friction, change in surface roughness, different wear phenomena. Alipio et al. [2021], Araya, N., et al. [2025], Fridman et al. [2007] and Verma, P., & Kumar, N. [2021].

The aim of this research was to analyze the design and maintenance of wind turbine gearbox systems exposed to lightning strikes. An analysis of existing gearbox design methods was the catalyst for proposing an alternative method that meets the goals of sustainable development and modernity.

How can we achieve efficient wind turbine gearbox designs and maintenance programs that meet sustainable development goals, focusing on equalizing the lifespan of amplifying gearboxes with that of wind turbines, increasing electricity generation and the profitability of wind energy in an environment with frequent lightning strikes?

The improvement proposals for wind turbine gearboxes were developed based on the authors' experience and considered real-time monitoring databases with machine learning and comparison of classified characterization models for interpretation and decision-making. The optimization of this technology will be the subject of future work

Research methodology

This research adopted a mixed approach, applying both quantitative and qualitative technologies, utilizing systematic processes, as well as records and estimated data.

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The aim of this investigation was to analyze the design and maintenance of wind turbine gearbox systems exposed to lightning strikes. To this end, the application of the quantitative method was relevant in identifying control variables involved in previous studies evaluating gearbox design and maintenance parameters, identifying critical factors such as intermittent torque and lightning strikes.

An analysis of existing gearbox design methods was the trigger for proposing an alternative method that meets the goals of sustainable development and modernity. Quantitative indices from gearbox design reports under current international regulatory frameworks determine, based on variables such as revolutions per minute, torque, load, lubrication type, diametral pitch adjustment, mechanical vibration frequency, and material mechanical properties, the design factors for traditional bearing and gear methods. Analysis of wind turbine operating curves based on mixed-methodology records determined that state-of-the-art gearboxes have an average replacement frequency of 0.4 times the lifespan of the wind turbine, which decreases the efficiency and productivity of the wind farm. Furthermore, the experiences of wind farm personnel qualitatively identify that damage to wind turbine amplifier boxes is primarily due to wear and lightning strikes, which cause a loss of efficiency in the wind turbine system.

This was linked to scientific reports, contrasting experience and statistics that were considered as the application of the mixed method, which allowed the possibility of obtaining results from the estimation of variables, which played an important role in decision-making to evaluate the useful life of a generator's gearbox. A mixed analysis was performed in the evaluation of design parameters and maintenance of gearboxes, identifying critical factors, intermittent torque and lightning discharges through quantitative and qualitative methods. The operational data resulting from this research determined that the improvement proposals for wind turbine gearboxes were carried out through the experience of the authors and considering real-time monitoring databases with machine learning and comparison of classified characterization models of gearbox systems with uses in the aerospace industry for interpretation and decision-making.

Finally, using a mixed method, an analysis of the control variables was carried out, which allowed us to address the question of how to achieve efficient gearbox designs for wind turbines and maintenance programs that meet sustainable development objectives, focusing on achieving equal lifespans of amplifying gearboxes with those of wind turbines, increasing electricity generation and the profitability of wind energy in an environment with frequent lightning strikes.

This research proposes a design of amplifying gearboxes for wind turbines using specialized techniques from the aerospace industry to generate thin-film coatings for ultrasonic equipment. It quantitatively evaluates technical parameters adaptable to the wind energy industry, allowing for increased mechanical properties in bearings and gear shafts to supply an expanding and growing wind energy industry with continuous threats of lightning strikes. Additionally, an autonomous gyroscopic balancing and leveling system was proposed for the equipment anchoring system inside the machine room. This system will reduce impacts on rotodynamic systems in the face of intermittent wind gusts and bending of the wind turbine base pedestal, greatly reducing impact cracking of materials and reducing abrasive, adhesive, and corrosive wear, fatigue failures, and surface pitting.

Qualitative methods were used to estimate the feasibility of these technologies for modern wind turbines. Quantitative and qualitative methods show that coating the wind turbine machine room equipment, mainly the amplifier box, with high mechanical strength thin films and gyroscopically balancing and leveling using autonomous systems reduces the impact between gear systems, bearings, and bushings. Furthermore, when used as a channel in the lightning discharge phenomenon, plasma is generated, but the ceramic coatings act as a protector of the substrate, experiencing less damage to its microstructure. In addition to this, the autonomous gyroscopic balancing and leveling systems have reduced impacts, which increases the useful life of the wind turbine gearbox in all its components. [Akgül, 2024, Al-Bedhany, J. H., et al. [2024], Doostmohammadi, M., et al. [2020], Farrando, M., et al. [2024] and Fridman et al. [2007].

Classification of gearboxes for wind turbines.

Multi-stage gearboxes for multi-megawatt wind turbines can be classified as two-stage planetary + single-stage helical [three stages total], three-stage parallel helical, compound configurations combining spur and helical gears, magnetic torque, cycloidal, hydrodynamic, and direct drive.

Wind turbine gearbox types include: Planetary [planetary gears around the ring gear, generating ratios of 30:1 to 100:1, compact, high torque capacity], Parallel Shaft [multi-mesh spur/helical gears, ratios of 30:1 to 90:1, simpler design, easier maintenance], and Hybrid [variable combination of planetary and parallel stages balances size, weight, and reliability].

The gear set [planetary or parallel] is made of high-strength alloy steel, the bearings are designed for axial and radial loads, seals and filters keep the lubricant clean, and advanced synthetic oils maintain the film under high pressures and temperature fluctuations. Adedeji, P. A., et al. [2024] and Araya, N., et al. [2025].

Active magnetic bearings; these bearings use electromagnetic fields to levitate and stabilize rotors, allowing for frictionless operation and self-balancing.

Magnetic transmissions: torque is transmitted via magnetic coupling, without mechanical contact; wear-free, lower torque density, zero gearbox failures, the need for lubrication is virtually eliminated, and availability and energy efficiency increase by approximately 10%. These have disadvantages: they are in the development stage, require a very large nacelle footprint, and require a high initial cost due to rare-earth magnets or large mass.

Cycloidal [strain wave] transmissions—a crescent-shaped rotor flexing on a stationary ring—generate very high reductions per stage, are less field-proven, and require complex seals. Hydrodynamic transmissions feature fluid coupling and torque converter stages, smooth torque transfer, overload protection, lower efficiency, and bulkiness.

Direct drive systems, by not having a gearbox, reduce mechanical noise and the number of rotating components.

Furthermore, this type of wind turbine has a single main bearing for the rotor and generator assembly, further reducing the number of moving parts and reducing maintenance and repair costs. Gearbox vs. Direct Drive. Direct drive systems have permanent magnets made of rare earths, neodymium, and can be used in small-scale wind turbines, but they also have applications in high-power wind turbines, both offshore and onshore. Previous studies have determined that direct-drive wind turbines of 7-10 MW require larger and heavier generators. In this case, a single- or two-stage gearbox is the best option and offers the same operating conditions.

Previous studies contrast mechanical transmissions with direct drives, where the role of mass, materials, and affordability influence the cost of the support structure. These groups of developers defend different positions, highlighting their advantages in terms of service life, indicating that the gearbox-based wind turbine is almost at its peak efficiency, while direct-drive turbines have more room for improvement.

The previous proposals are in dispute; however, both proposals have significant growth potential within their areas and combined, will be superior in future technology developments. But the problem to overcome is lightning strikes, for which neither proposal is prepared to operate without repairs during the wind turbine's planned lifespan. NFPA. [s.f.]. NFPA 780.

Traditional mechanical design methods for gearbox design

Traditional mechanical design methods for gear design specify that the first thing to be known are design environment conditions which are key input and output: input speed, torque, power, direction of rotation, output speed, torque, power and type of motion desired, operating conditions [temperature, lubrication, duty cycle], space constraints, weight, noise and efficiency are essential to select the gear type, gear ratio and materials.

Select the gear geometry that best suits your application: spur, helical, helical, bevel, worm. Consider load carrying capacity, size, noise, and mounting configuration when making your decision.

Determine the gear ratio, select the standard tooth size [modulus or diametral pitch], calculate pitch diameters, verify center distances, select the appropriate pressure angle, clearance for the lubricant to be used, tooth profile, interference and clearance [involute profile], radial height above the pitch circle [addendum], radial depth under the pitch circle [dedendum], clearance between the tip and root [clearance], angle between the line of action and the tangent on the pitch circle [pressure angle], contact depth [working depth].

Avoid interference by ensuring the minimum number of teeth meets AGMA 2001-D04 for a given pressure angle and profile offset. Clearance [typically 0.05 to 0.15 mm] ensures smooth rotation and compensates for thermal expansion and tooth deflection. Strength analysis and AGMA classifications, strength checks; bending stress, contact stress [Hertzian], applying dynamic, load, size, and reliability factors, converting these allowable stresses into a safety factor against fatigue and pitting. material selection and heat treatment, manufacturing methods, assembly, alignment and lubrication, maintain correct center distance and shaft alignment to minimize vibration and noise, adjust backlash within recommended limits for thermal expansion and tooth deflection, choose lubricant type [oil, grease, solid film] based on speed, load and temperature and finally prototype verification and testing, stress re-evaluation with refined loads [dynamic, impact], finite element analysis and continuous evaluation of the system based on its experimental development until the expected performance target is reached in a sustainable and sustainable optimization. AGMA. [2004]. AGMA 2001-D04 and Araya, N., et al. [2025].

Design of gearboxes for wind turbines.

The wind power propulsion system has a turbine whose load is not perfectly uniform. Implementing an equivalent load with various load levels must be done with multifunctional design models and safety factors against fatigue and pitting, based on the environment and exposure to chaos theory phenomena, as this can lead to inaccurate results when assessing fatigue. AGMA 6006 includes a method for calculating gearbox reliability and also addresses how to address other failure modes. AGMA. [s.f.]. AGMA 6006 and Jiang, L., et al. [2020].

Numerical simulation combines finite element gear stress models with plasma arc CFD to predict local heating and erosion, in-situ monitoring incorporates thin-film sensors on critical tooth surfaces to detect arc events and quantify material loss over time, multidisciplinary cross-sector collaboration analyzing experience from the wind turbine and aerospace sectors, where plasma arcs on metal frequently result in advanced mitigation tactics.

By combining gear geometry, load rating standards, lightning protection protocols, and high-energy discharge testing, drives can be created that are resilient to the mechanical stresses and extreme conditions of lightning-induced plasma.

Multidimensional failure modeling and optimization based on the classic Stribeck curve of planetary gearbox bearings, pins to prevent wear failures and reduce friction in wind turbines, have proposed a unified failure model based on a tribodynamic framework for full-size gearbox bearings. The proposed multidimensional designs achieve reductions of more than 90% in friction and wear failures, closely matching wear patterns that improve stability and wear resistance of the radial clearance observed in tests. This represented an improvement in the regulation of oil film thickness in the critical transition zone.

Hydrodynamic and mixed lubrication regimes in gear shafts, bearings, and bushings reduce friction coefficients at contacts, thermal effects, and thermoelastic deformation. Lower clearance ratios and higher width-to-diameter ratios alleviate stress concentrations at the edge. Al-Bedhany, J. H., et al. [2024].

Replacing rolling bearings with plain bearings and integrating them with planetary gears can increase the torque density of wind turbine transmission systems. However, planetary gears are subjected to complex forces and moments arising from the dynamic meshing of internal and external gear pairs. This results in edge contact in the plain bearings, feedback effects in the mesh, load skew, strong inter-gear coupling, and critical lubrication.

Asymmetric deformation of the support pins under dynamic meshing forces results in skewed mesh loading and edge contact, which intensifies the increase in input torque.

Optimizing skewed mesh loading and edge contact of the bearing reduces loading conditions, improving load distribution and the performance of the wind turbine gearbox shown in Figure 1.

Box 1

Gearbox test bench top view diagram:

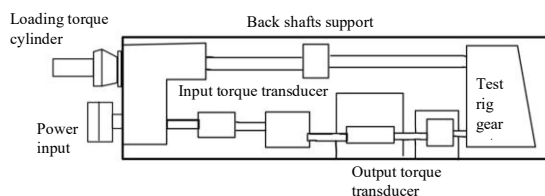


Figure 1

Gearbox system for wind turbine

Source: Own elaboration

Lightning strikes on wind turbines.

Lightning strikes to wind turbines over their lifetime were estimated by previous studies at 20 years and are divided into low-risk scenarios with 12 events, medium-risk scenarios with 20 events, and high-risk scenarios with 200 events. Factors affecting the number of strikes include turbine height, geographic location, and lifetime.

Lightning and high-voltage faults can create a transient plasma arc carrying tens to hundreds of kiloamperes and temperatures exceeding 20,000 K. This plasma expands supersonically, emits intense electromagnetic fields, and generates powerful shock waves. When such an arc touches a gear system or gearbox housing, it can cause complex damage that goes far beyond simple superficial burns.

Factors influencing the severity of lightning damage: current waveform: short, high-peak return strokes [μs] cause deeper, sharper craters; longer continuous currents [hundreds of μs] provide more total heat and wider melting zones, resulting in greater total charge transfer; greater charge results in higher energy deposits, thicker melt layers, and larger heat-affected zones. Cernalevschi, G., et al. [2025], and Farrando, M., et al. [2024].

Gears made of high-conductivity steel and hardened alloys are more prone to cracking. Protective and lubricating coatings: Dielectric paints delay arc formation but can trap energy, causing the coating to explode. Grounding and enclosure design: Well-sealed housings deflect arc paths away from sensitive gear surfaces.

Transient currents induce electromagnetic Lorentz forces that can bend fine metal teeth or demagnetize bearings. Bruce, T., et al. [2015] and Cernalevschi, G., et al. [2025].

Mitigation strategies include installing a robust ground and bonding system to provide a low-resistance arc path to the chassis or ground, thus avoiding the gears; enclosing gear trains in conductive housings or Faraday cages to intercept arcs externally; and applying arc-resistant coatings [thin, high-hardness, conductive films] that vaporize in a controlled manner, thereby reducing direct damage to the steel. Agbogo, V. U., et al. [2025].

Recommendations after a lightning strike: install surge protection on nearby power supplies to minimize stray current faults; implement condition monitoring [ultrasonic inspection, ink penetration testing, hardness mapping] after any severe electrical event.

Beyond immediate repairs, arc erosion test benches are worth exploring to quantify material loss under current waveforms. This data helps predict service life after an impact and refine maintenance intervals for critically damaged gear systems. Cernalevschi, G., et al. [2025] and Zhang, W., et al. [2025].

Standards for the design of gearboxes, bearing and bushings exposed to lightning discharges.

International standards for wind turbines exposed to lightning strikes. IEC 61400-24:2019 Wind power generation systems Part 24: Lightning protection specifies requirements and guidelines for the protection of wind turbines and complete wind power systems against the direct and indirect effects of lightning. It defines the lightning discharge environment for wind turbines, establishes risk assessment procedures, and sets out protective measures, test methods, and recommendations. Alipio et al. [2021] and IEC. [2019]. IEC 61400-24:2019.

To design mechanical or electromechanical gear systems that may be exposed to lightning strikes, two families of international standards are used: general lightning protection principles and test methods, and application-specific requirements [for wind turbines, vehicles, aircraft, etc.].

General rules for lightning protection and surge immunity; IEC 62305-1 - 2021, Lightning protection - General principles, risk management, definitions, and lightning parameters. IEC 62305-2 - 2021; Lightning protection - Risk management methodology for assessing lightning risk to structures/equipment. IEC 62305-3 - 2021; Lightning protection - Physical damage to structures and life-threatening lightning strikes - Protection of external systems [air termination, downconductor, earthing]. IEC. [2021]. IEC 62305-1:2021, IEC. [2021]. IEC 62305-2:2021, IEC. [2021] and IEC 62305-3:2021.

Wind turbine gearboxes IEC 61400-24:2019; Wind turbine generator systems - Part 24: Lightning protection addresses lightning strikes to blades, nacelles, and internal surge mitigation for control and power electronics. IEC. [2019]. IEC 61400-24:2019.

International standards for the design of gears that may be exposed to lightning-induced plasma arcs require combining traditional gear engineering standards with lightning protection and high-energy discharge testing standards. ISO 6336, Load-carrying capacity calculation of spur and helical gears, defines safety factors for bending and pitting, material properties, and design formulas. ISO 1328, Precision of involute cylindrical gears, specifies tolerances for tooth profile, helix, and pitch to ensure accurate meshing. AGMA 2001-D04, Fundamental classification factors and calculation methods, the American equivalent of ISO 6336, which includes fatigue factors for surface cracking and wear. AGMA. [2004]. AGMA 2001-D04, Bru, K., et al. [2020], ISO. [2019]. ISO 1328 and ISO. [2019]. ISO 6336.

Lightning protection and risk management IEC 62305 lightning protection, NFPA 780 standard for the installation of lightning protection systems and guides on air terminals, down conductors, bonding and grounding. IEC. [2021]. IEC 62305-1:2021.

High-energy discharge and plasma testing IEC 60068-2-60 Environmental testing - Mixed gas flow corrosion test, adapts to electrode erosion testing by simulating the impact of a plasma jet. IEC 61000-4-5 Electromagnetic compatibility, Surge immunity test defines the generator output for high-energy transients, useful for emulating impact currents.

IEC 61400-24 Wind turbines, Lightning protection, although focused on blades, details plasma arc adhesion and material erosion.

Aerospace and Transportation Applications RTCA DO-160, Section 22 Environmental Conditions and Test Procedures - Lightning-Induced Transient Susceptibility addresses the indirect effects of lightning strikes on mechanical and electrical assemblies. SAE ARP5412A Guidelines for Aircraft Lightning Protection describes test setups for direct-strike plasma arc interaction with metallic parts. Bru, K., et al. [2020], Cernalevski, G., et al. [2025], IEC. [2000]. IEC 60068-2-60, IEC. [2014]. IEC 61000-4-5 and SAE. [s.f.]. SAE ARP5412A.

Integrating standards into the gear design workflow: Risk assessments apply IEC 62305-2 to determine the likelihood and severity of lightning strikes at the facility. Mechanical design: Use ISO 6336/AGMA 2001 to size gears for torque and fatigue life, considering potential plasma erosion. Material and coating selection: Choose steels or nickel-based alloys with proven resistance to plasma arc erosion; consider thermal spray coatings according to ISO 14916. Protective measures: Connect gear housings to down conductors; ensure equipotential bonding according to IEC 62305-4. Laboratory tests: Overcurrent simulation according to IEC 61000-4-5 on gear shafts.

Perform plasma jet erosion tests according to the modified IEC 60068-2-60 standard. Check the accuracy of the gears after testing against the tolerances of ISO 1328. AGMA. [2004]. AGMA 2001-D04, IEC. [2000]. IEC 60068-2-60, IEC. [2014]. IEC 61000-4-5, IEC. [2021]. IEC 62305-1:2021, IEC. [2021]. IEC 62305-2:2021, IEC. [s.f.]. IEC 62305-4, ISO. [2010]. ISO 14916, ISO. [2019]. ISO 1328, ISO. [2019]. ISO 6336 and ISO/AGMA. [s.f.]. ISO 6336/AGMA 2001.

The ISO 4406:99 4/6/14 μm standard is used to classify the cleanliness of hydraulic oil [or similar fluids] based on the amount of particles it contains in μm . ISO. [1999]. ISO 4406:99.

Failure rate in onshore and offshore wind turbine gearboxes

A previous assessment of offshore, floating, semi-submersible, and stationary wind turbines estimated that the failure rate for electrical and electronic components and blade systems is seven times higher than that of land-based turbines. However, the approximate annual failure rate for the gearbox and drive train system was estimated to be about four times higher than that of land-based turbines. Baragetti, S., et al. [2011].

The adverse operating conditions of semi-submersible and fixed floating offshore wind turbines determined that failures have a greater incidence in the support structures, hydraulic system, gearbox, generator, and other systems.

These are due to factors such as salt spray, waves, high wind speed, and others. Early fault detection allowed for the implementation of predictive maintenance strategies for the most critical systems, such as corrective maintenance in gearboxes, generators, turbine blades, and hydraulic systems that require longer downtimes. Maintenance strategies were implemented with cause-and-effect analysis of failures, as part of a plan to improve the design and optimize maintenance programs.

In semi-submersible and fixed floating offshore wind turbines, it was identified that the mooring system - support structures [mooring line breakage, abnormal tension of turnbuckles, failure of anchor, buoys and fairleads] were the most prone to failure components with a rate of 17%, failures to hydraulic and pitch systems have a failure frequency around 13%, the generator with a frequency 12%, the gearbox and speed train with 8% representing the failures with the greatest downtime due to repair that influence the performance of the wind turbine with impacts on the production of the wind farm.

On the other hand, failures of lesser incidence are electronic components, blades, and blade yaw system. Cardoni, M., et al. [2021] and Farrando, M., et al. [2024].

The frequency of failure in wind turbine amplifier box systems considering a useful life of 20 years, with respect to CMMS/SCADA [Computerized Maintenance Management System/ Supervisory Control and Data Acquisition] inspection databases, manufacturer recommendations and statistics is; oil change and filter replacement every [0.1, 0.25] complete gearbox disassembly and rebuild every [0.15, 0.4], drive train failure 0.03 and bearing failure 0.028, media leakage 0.78, mechanical vibration 0.13, sensor failure 0.001, abrasive wear 0.24, gear fatigue 0.06, bearing pitting 0.06, poor lubricating oil quality 0.04, abnormal filter 0.04, gear pitting 0.04, poor gear tooth design 0.04, excessive pressure 0.04, gear tooth deterioration 0.02, and over temperature 0.018. you can see figure 2. Hu, Q., et al. [2017].

Box 2

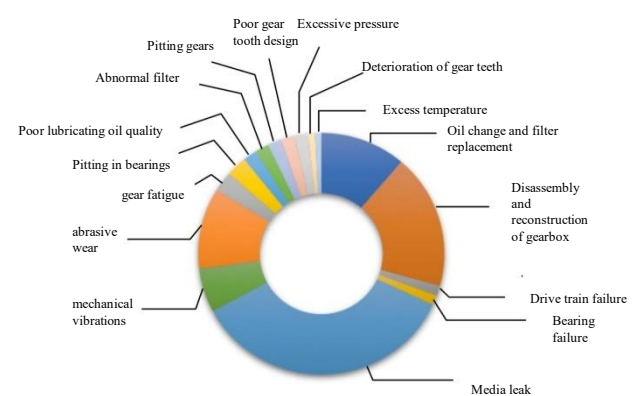


Figure 2

Failure frequency in wind turbine amplifier box systems considering a useful life of 20 years.

Source: Own elaboration

Damage mechanisms in gears, bearings and bushings of wind turbines

Gear damage mechanisms generated by thermal effects cause localized melting and vaporization at the arc junction, producing craters, pitting, grain growth, hardness reduction, and embrittlement. Repeated or prolonged current pulses deepen the molten layer and widen the heat-affected zone, developing mechanical effects; supersonic plasma expansion, pressure shocks in the metal, microcracks, and subsurface delamination. Furthermore, magnetic [Lorentz] forces from the arc current can deform thin-walled gear teeth or initiate fatigue cracks. High-velocity plasma jets erode sharp edges and surface asperities.

Eddy currents induced in specific areas of the gear cause volumetric heating, intensifying thermal, stress and electromagnetic gradients, and distorting tolerances between parts and within the part.

Chemical and metallurgical effects promote rapid oxidation of the freshly molten metal, forming brittle oxides that delaminate under load.

Nitrogen and other atmospheric ions can be absorbed by the heat-affected zone, altering the microstructure and corrosion resistance.

Thin films and their properties at high temperatures applied to mechanical transmissions of wind turbines.

Thin films are a mitigation strategy, using plasma-resistant alloy substrates [stainless steel such as 316L or nickel-based superalloys], hard ceramic or diamond-like carbon [DLC] coatings to protect against sputtering and arc pitting, alumina insulating barrier coatings on non-drive surfaces to prevent unwanted discharges, round tooth edges and avoid sharp corners to reduce field intensification factors, introduce local grounding electrodes or Faraday cages around the gearbox to deflect stray discharges from the gears, implement adequate insulation on shafts or housings to control where plasma can form, use solid lubricants [molybdenum disulfide and graphite or those that resist plasma attack. Agbogo, V. U., et al. [2025], Amaro, R. I., et al. [2005], Bobzin, K., et al. [2015], Bobzin, K., et al. [2015] and Yu, B., et al. [2024].

Plasma ion nitriding is used to harden gears and shafts in the aerospace industry operating in high-altitude, low-pressure environments. Plasma-resistant coatings [ceramic thermal barriers] protect rotating components from ionized gas erosion and thermal cycling in the industry. Gear systems near plasma-exposed components are coated with tungsten carbide or DLC to resist neutron bombardment and plasma-induced erosion.

High-temperature ceramic matrix composites are used in gear housings and bearing housings to withstand extreme thermal loads. Originally developed for turbine blades, these composites have now been adapted for compact, high-temperature gearboxes to operate at temperatures up to 1200°C without significant thermal deformation.

Diamond-like carbon [DLC] surface engineering coatings offer a combination of mechanical and chemical benefits. This amorphous carbon material with diamond-like properties, extreme hardness, low friction, and high chemical resistance. It contains mixtures of sp^2 [graphite] and sp^3 [diamond] carbon bonds, giving it a unique balance of toughness and lubricity. DLC is deposited by physical vapor deposition [PVD] or chemical vapor deposition [CVD]. Substrates are placed in a vacuum chamber where carbon ions are accelerated and implanted onto the surface, forming a uniform, ultra-thin film a few microns thick. DLC coatings offer a low coefficient of friction <0.1 , reducing wear and energy loss, which is essential for automotive and aerospace parts.

High hardness protects components from abrasion and corrosion resistance, and is applied under ISO 4406:99, ISO 14577-1/-2/-3:2015, and ASTM F1578-18 standards. ASTM. [2018]. ASTM F1578-18, Baragetti, S., et al. [2011], Bobzin, K., et al. [2015], ISO. [1999]. ISO 4406:99, ISO. [2015]. ISO 14577-1/-2/-3, Latha, S., & Surendar, S. [2023], Latha, S., & Surendar, S. [2023] and Yu, B., et al. [2024].

Lubricants for transmission exposed to plasma environments.

Lightning discharges generate plasma channels with ion bombardment that dislodge atoms from gear teeth and rolling elements/races in bearings, altering profiles and increasing clearance. High-energy neutrals and radicals chemically erode surfaces over time. The sharp edges of deformed teeth and rolling elements on bearing races concentrate electric fields, causing microarcs that pit the metal. Return currents or discharge paths can traverse lubricated spaces, degrading gears, bearings, and lubricants.

Reactive plasma species [O, OH, F, Cl] attack and degrade conventional lubricants [semi-solid, liquid, gaseous-nebula states], acidifying them, or carbonizing them to form sludge. Vacuum or low-pressure plasmas completely eliminate lubricants, generating thermal and mechanical stress. Localized heating of the discharges can induce thermal cycling and microcracks. Increased friction due to surface roughness amplifies wear. Araya, N., et al. [2025].

Gears exposed to plasma environments use solid lubrication [MoS₂ or graphite], which performs better than fluid lubricants. Ag-Mo, FeTiO₃, composite coatings form lubricating films that can withstand over 800°C under plasma exposure, ideal for hypersonic vehicle gearboxes. Extreme temperatures can exceed 1000°C.

Gearbox housings and internal components must resist thermal distortion and maintain lubricant integrity. Motors and actuators require compact gearboxes that deliver hundreds of kW per kilogram. Achieving high torque in a confined space tests gear strength and bearing life. Araya, N., et al. [2025], González Prieto, D., et al. [2021], Kozień, E., & Grzegorzczak, M. [2020] and Ma, Y., et al. [2020].

In vacuum or low-pressure plasmas, it is advisable to use thin films of ionic-coated MoS₂ or gold-coated coatings as a solid-film solution. It uses self-healing lubricants, such as ionic liquids with high oxide stability that resist radical bombardment. Smart lubrication systems; nano-enhanced lubricants [incorporating graphene or boron nitride, polytetrafluoroethylene [PTFE], to reduce friction and wear at high temperatures], self-healing lubricants [which react chemically to repair microabrasions on gear surfaces], and real-time oil condition monitoring [sensors integrated into the gearbox detect degradation and trigger adaptive responses]. Graphenes in oils increase the heat transfer rate by 31.91%, increase viscosity and performance, strengthen lubricants for wind turbine gearboxes, optimal graphene loading varies between [0.1, 4] wt% depending on base oil viscosity and operating conditions, high shear mixing or ultrasonic treatment ensures uniform distribution. Ahsan, A., et al. [2025], Gulzar, M., et al. [2015], Jin, X., et al. [2024], Kozień, E., & Grzegorzczak, M. [2020], Ma, Y., et al. [2020] and Zouina, O., et al. [2025].

Previous studies of oils in wind turbine amplifier gearboxes identified oil properties. The oil degrades for up to 16 years, but does not lose its lubricating properties, making it functional for use. However, the addition of additives [corrosion inhibitors and antifoam agents] is recommended to improve its properties. It is also worth mentioning that these studies were conducted in a laboratory under controlled environmental conditions and without the presence of lightning strikes.

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They also identified premature failure of the gearbox bearings, which continue to fail between 5% and 20% of their useful life. This indicates that the lubricant loses shear properties and, tribologically, loses load conditions that are fundamental to the contact clearance damping phenomenon. Kozień, E., & Grzegorzczak, M. [2020] and Kumar, R., et al. [2023].

Autonomous base balancing and leveling systems for industrial machinery

Gearboxes in wind turbines accelerate the slow rotation of the turbine blades to the high speed required by electric generators. A gear ratio of 90:1 transforms [7, 16] rpm in the rotor into 1500 rpm in the generator.

Design challenges: it must withstand large moments, torque fluctuations, and severe transient loads from power grid startups, shutdowns, and events. Misalignment under high loads causes stress concentrations, leading to gear or bearing failures, as shown in Figure 3. Al-Bedhany, J. H., et al. [2024] and Bruce, T., et al. [2015].

Box 3

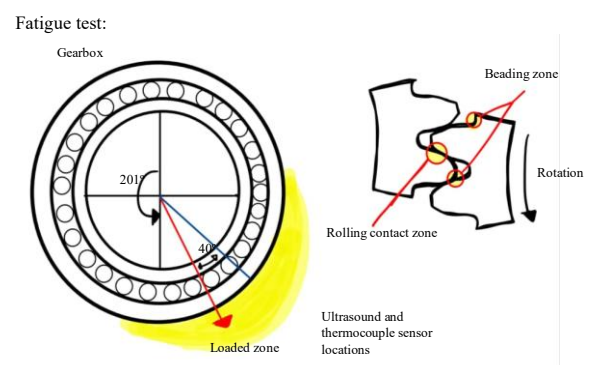


Figure 3

Areas of greatest damage in bearings and gears.

Source: Own elaboration

Offshore wind energy takes advantage of the high intensity of oceanic winds. As energy demand grows, larger turbines are required to optimize generation and reduce the cost of renewable electricity. On the other hand, the engineering challenge, particularly in the design of pedestal-type structures, is that they must withstand greater structural loads such as wind gusts while maintaining structural integrity, profitability, and transportability.

A sustainable development analysis supported by monitoring using digital twin technology, powered by artificial intelligence, can revolutionize the optimization of tower design based on zonal deformation under radial and mixed loads that influence the leveling of the wind turbine and its components, as shown in Figure 4. Ding, Y., et al. [2025].

Box 4

Deformation diagram of wind towers:

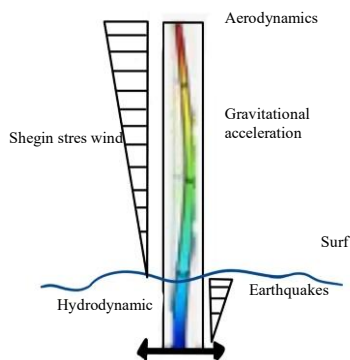


Figure 4

Deformation of towers by zones under radial and mixed environmental loads

Source: Own elaboration

Autonomous balancing and leveling systems for industrial or aerospace machines automatically monitor and correct imbalance and misalignment of rotating aerospace components [propellers, turbine rotors, driveshafts] during operation. By integrating real-time sensors, control algorithms, and actuators, these systems ensure optimal rotor dynamics, reducing vibration, noise, and structural fatigue. Aerospace components operate at very high speeds and within tight tolerances. Unbalanced rotors amplify vibration, reduce performance, and accelerate wear. An automatic balancing and leveling system seeks lightweight, highly stable structural designs that minimize additional mass and part count, meeting the stringent requirements of aeroengines and transmissions.

High-precision accelerometers, or vibration probes, measure synchronous vibration amplitudes and phase angles in one or more planes. These have aerospace applications, such as gyroscopes for inertial navigation and satellite stabilization platforms, microturbines and high-speed ventilation devices in avionics cooling, helicopter rotors [main and tail] and fixed-wing propellers, turbine and compressor discs in jet engines, drive shafts and power take-off assemblies. Coronado, D., & Kupferschmidt, C. [2014].

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The working principle of a self-contained balancing and leveling loop captures the amplitude and phase of vibration via vibration sensors, base mounted piezoelectric accelerometers detect the amplitude and phase of the unbalanced vibration in real time, inclinometers/gyroscopes, MEMS [Microelectromechanical Systems] or fiber optic gyroscopes continuously measure the roll and pitch angles of the base enabling angulation leveling control, control unit, real-time signal processor, a high-speed DSP [Digital Signal Processors] or FPGA [Programmable Gate Arrays] reads the sensor data, executes balancing/leveling algorithms, and issues actuator commands with millisecond latency adaptive algorithms, combination of PID [Proportional-Integral-Derivative control] loops for fast correction with model-based observers that distinguish between true unbalance and transient disturbances, actuation layer, Electromagnetic balance actuators generate counter-rotating magnetic forces that directly oppose imbalance vectors, ideal for high-frequency corrections without adding moving mass.

Hydraulic/pneumatic leveling cylinders. High-rigidity cylinders adjust base height at multiple corners; solenoid valves regulate flow according to control needs. Adjustable mass carriers: Motorized sleds carrying removable masses are repositioned around the spindle to rebalance rotating components. AI-based adaptive controls: Hybrid controllers that combine the simplicity of PID with the adaptability of reinforcement learning, automatically adapting to changing dynamics. Edge computing and 5G [machine learning or blockchain]: Offloading heavy estimation and planning tasks to edge servers, enabling lighter embedded computers and more complex algorithms. Bio-inspired mechanisms for optimization offer forward-looking learning capabilities. González, M. J., et al. [2021].

International standards for autonomous balancing and leveling systems applicable to wind turbine systems: SAE ARP 4048; Horizontal rigid bearing balancer for aero-components, SAE ARP 4050; Vertical rigid bearing balancer for discs and rings, SAE ARP 5323; Test methods for vibration measurement on rotating machinery, ISO 1940-1; Balance quality and permissible residual unbalance, IEC 62832.

Berra-Ceballos, Raúl, Cruz-Gómez, Marco Antonio, Mejía-Pérez, José Alfredo and Castillo- Pensado, Juan Luis. [2025]. Design and maintenance analysis of wind turbine amplifier gearboxes systems exposed to lightning discharges. Journal-Mathematical and Quantitative Methods. 9[15]1-16: e3915116.

<https://doi.org/10.35429/JMQM.2025.9.15.3.1.16>

Establishes a framework for digital factory architectures, including digital twin elements for level sensing modules and adaptive control systems that maintain machine or platform levelness in real time; and IEC 60204-1; Covers the safety of machine electrical equipment, specifying requirements for control circuits and monitoring devices used in automated leveling systems. Al-Bedhany, J. H., et al. [2024], Bruce, T., et al. [2015], Ding, Y., et al. [2025], Hu, Q., et al. [2017], IEC. [2016]. IEC 60204-1, IEC. [2016]. IEC 60204-1, IEC. [2016]. IEC 62832, IEC. [2016]. IEC 62832, ISO. [2006]. ISO 1940-1, SAE. [s.f.]. SAE ARP4048, SAE. [s.f.]. SAE ARP4050, SAE. [s.f.]. SAE ARP5323 and SAE. [s.f.]. SAE ARP5412A.

Proactive maintenance of wind turbine amplifier boxes with the support of artificial intelligence [AI]

Wind turbine maintenance programs begin at the beginning of their useful life, in an initial phase of 0-5 years; manufacturing defects are identified, a performance baseline is established. In the intermediate life phase, corresponding to 5-20 years, uptime is maximized and wear is addressed. Finally, in the final life stage of 20-25 years, conservation maintenance is carried out to enable safe and profitable operation with a planning approach to a decommissioning program aligned with circular economy objectives. Verma, P., & Kumar, N. [2021].

Strategies to extend service life: dust and moisture-proof housing sealing, high-reliability HVAC or fan systems, surge protection units, remote monitoring: SCADA status indicators for early warnings, solid-state MOSFET or SSR [MTBF] replacements. Digital twins: simulating thermal and vibration profiles to optimize preventive maintenance. Consider amplifier enclosures as mid-life consumables. Agbogo, V. U., et al. [2025], Araya, N., et al. [2025], Arias Velásquez, R. M. [2024], Bobzin, K., et al. [2015] and Ding, Y., et al. [2025]. For monitoring and maintenance, install active cooling [liquid or conduction] near high-flow areas to buffer temperature spikes; incorporate voltage/current sensors to detect the onset of electrical arcing in real time; schedule periodic inspections using optical profilometry or scanning acoustic microscopy to detect early erosion; implement a predictive maintenance algorithm based on operating hours, discharge counts, or cumulative plasma exposure.

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Digital twins: Virtual replicas of geared powertrains that enable real-time load optimization. You can see Figure 5. Doostmohammadi, M., et al. [2020], González Prieto, D., et al. [2021], Gulzar, M., et al. [2015], Jin, X., et al. [2024], Verma, P., & Kumar, N. [2021], Yu, B., et al. [2024] and Zouina, O., et al. [2025].

Box 5

wind turbine component:

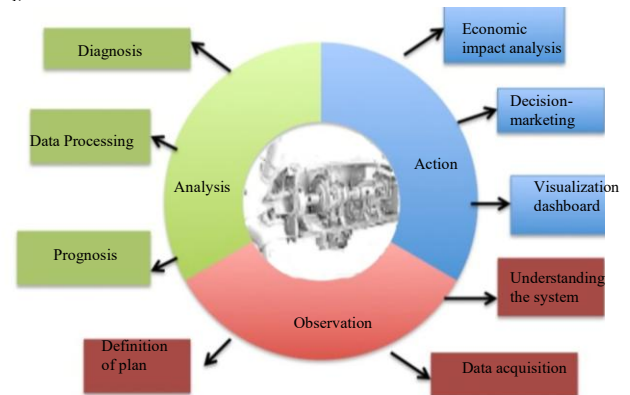


Figure 5

Real-time monitoring of wind turbine systems and components.

Source: Own elaboration

Wind turbulence can cause enormous stress on wheels and bearings. The faster the wind, the more vulnerable the gearboxes; offshore turbines are more exposed than onshore ones.

Wind turbine gearboxes face severe stresses due to temperature fluctuations, humidity, vibrations, and system transients. The presence of 0.01% water in the oil reduces oil life to 66%, 0.05% to 38%, and 0.15% to 20%. This represents a latent problem in gearbox systems, shortening gearbox life.

AI models predict failure modes before they occur, enabling proactive maintenance. Gearboxes now include integrated vibration and temperature sensors. Surface roughness measurement provides valuable information on slippage failures; the shape of the roller impact zone confirms deflection and misalignment throughout the bearing's rotation. Indentation, on the other hand, depends on contact pressure rather than debris size. Coronado, D., & Kupferschmidt, C. [2014], Farrando, M., et al. [2024], González, M. J., et al. [2021], Hu, Q., et al. [2017] and Zhang, W., et al. [2025].

Replacing a turbine gearbox represents approximately 10% of the cost. Turbines are designed for a 20-year lifespan, but many gearboxes fail after about five years due to fatigue, micropitting, and lubrication failure. The downtime from replacement impacts profitability and energy efficiency. Arias Velásquez, R. M. [2024] and Cardoni, M., et al. [2021].

Gearbox efficiency affects net power output; advanced tooth profiles and low-viscosity lubricants are key to increasing efficiency. Gearbox design varies for marine and onshore turbines; the role of digital twins in proactive maintenance. Ding, Y., et al. [2025], Kumar, R., et al. [2023] and Zhang, W., et al. [2025].

Conclusions

This research study fulfills its objective of analyzing the design and maintenance of wind turbine gearbox systems exposed to lightning strikes. It presents the contribution that wind turbine gearbox systems have evolved to meet the growth and expansion of the wind energy industry, along with the challenges it faces. The results of the analysis determined that traditional design methods under international standards establish the design bases for wind turbine amplifier boxes based on dynamic safety factors for each of their components. However, the wind turbine gearbox system and its components face a major challenge in lightning strikes [transient currents].

In the event of this phenomenon, the mechanical transmission is part of the grounding plasma channel, exposing its components to high temperatures, causing premature wear and reducing their useful life. In order to solve this problem, this research contributes that existing technologies for the aerospace industry should be used, such as the coating of thin films of ceramic or diamond-like carbon [DLC] on stainless and duplex steel superalloy substrates, to protect against sputtering and plasma-resistant arc pitting, in addition to the use of nano-enhanced intelligent lubrication systems [incorporating graphene or boron nitride, solid MoS₂ or graphite, Ag-Mo, FeTiO₃, PTFE [Polytetrafluoroethylene] that resist high temperatures in the event of transient discharges.

It is worth mentioning that the authors' proposal to incorporate an autonomous gyroscopic balancing and leveling system used in the aerospace industry and that has not been used for the anchoring system of equipment inside the machine room of wind turbines, will allow intermittent wind gusts and bending of the pedestal of the base of the wind turbine to mitigate the impacts on the rotodynamic systems, greatly reducing cracking.

The impact of materials, abrasive, adhesive, and corrosive wear, fatigue failures, and surface pitting will extend the lifespan of the gearbox system, similar to the lifespan of the wind turbine. The growth of wind turbines means that the technologies that must be used are the same as those used in the aerospace industry, with their adaptations to international standards, and the idea that a wind turbine is a simple machine for generating electrical energy with reduced costs that can be scaled with the same basic infrastructure conditions is abandoned.

The sustainable development of a wind farm lies in generating a sustainable balance based on the advanced technologies demanded by the equipment's operating environment.

Declarations

Conflict of interest

The authors declare no interest conflict. They have no known competing financial interests or personal relationships that could have appeared to influence the article reported in this article.

Author contribution

Berra-Ceballos, Raúl: Contributed to the research idea, information gathering, and writing of several sections of the article, based on his professional experience.

Cruz-Gómez, Marco Antonio: Contributed to the revision of the project's writing and provided general improvement suggestions, based on his professional experience.

Mejía-Pérez, José Alfredo: Contributed to the revision and writing of various sections, based on his professional experience.

Castillo-Pensado, Juan Luis: Contributed to the revision and writing of various sections, based on his professional experience.

Availability of data and materials

This article is a literature review based on previously published data and documents. No new datasets were generated during this study.

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Abbreviations

AI - Artificial Intelligence

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