AI-Driven Load Sensing for Wind Turbine Operations

Cost-Effective Solutions for Turbine Reliability

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Monitoring drivetrain loads is essential for reliable wind turbine operations, yet traditional methods rely on complex rotating sensors. This paper highlights the industrial relevance of AI-driven virtual sensing, utilizing a static sensor setup and machine learning models trained on real-world data to optimize turbine reliability, reduce costs, and enhance operational predictability.

Introduction: Why Reliable Load Monitoring Matters

The reliable operation of wind turbines is critical to achieving the global shift toward renewable energy. At the heart of turbine reliability lies the ability to accurately monitor drivetrain loads-forces and moments that directly impact the gearbox, one of the most failure-prone components. Despite their importance, drivetrain loads are rarely measured in operational wind turbines due to the cost and complexity of traditional measurement methods [1]. This gap undermines turbine reliability, increases maintenance costs, and limits opportunities for proactive management of component health. Drivetrain failures significantly contribute to operational and maintenance costs, accounting for as much as 34 percent of the levelized cost of energy (LCOE) in offshore wind farms [2]. Current condition monitoring systems (CMS), commonly used in wind farms, detect damage after it has occurred but do not provide real-time insights into dynamic drivetrain loads [3]. For instance, traditional rotating sensors required for direct load measurements are expensive to install, prone to wear, and difficult to maintain, particularly in offshore environments [1, 4].

This challenge is not merely technical – it has profound economic and environmental implications. Unpredictable and site-specific dynamic loads often cause deviations from design expectations, leading to accelerated drivetrain wear and unplanned maintenance. Studies reveal that site-specific wind speed distributions can differ by up to 35 percent from design assumptions, further complicating reliability assessments [3]. These issues increase maintenance costs, comprising 1.5 to 3 percent of turbine investment costs annually. They can lead to the early replacement of key components, raising operational costs and environmental impacts [3].

Recognizing these challenges, integrating AI and virtual sensing marks a paradigm shift in monitoring drivetrain loads. Leveraging static sensor setups and advanced machine learning models, this technology addresses the core limitations of traditional systems. Offering real-time, actionable insights into drivetrain behavior empowers operators to make proactive, data-driven decisions to enhance turbine reliability, reduce costly downtime, and extend the lifespan of critical components.

This paper explores the transformative potential of AI-driven virtual sensing, validated using the 4 MW wind turbine drivetrain test rig at the Center for Wind Power Drives in Aachen, Germany. By simulating real-world conditions, this approach demonstrates its ability to accurately estimate drivetrain loads while eliminating the need for complex rotating sensors. The findings highlight a cost-effective and scalable solution designed to bridge the gap in drivetrain monitoring technologies, paving the way for enhanced operational efficiency and sustainability in wind energy.

The Current Gap in Load Monitoring Technologies

Despite the critical role drivetrain load monitoring plays in ensuring wind turbine reliability, current technologies have significant limitations that hinder their widespread adoption. Traditional methods

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often rely on direct load measurement using rotating sensors, which are costly, complex to install, and prone to wear and failure, particularly in challenging environments such as offshore wind farms [1, 4]. These sensors require significant investment and present logistical challenges during installation and maintenance, further increasing operational expenses [4].

Condition Monitoring Systems (CMS), commonly used in the industry, offer a partial solution by identifying drivetrain damage post-occurrence. However, they cannot measure dynamic loads directly or provide real-time predictive insights [1, 3]. For example, current CMS approaches typically monitor secondary indicators, such as vibration or temperature, which do not provide a complete picture of the forces acting on critical drivetrain components [1, 4].

This gap has a measurable impact on turbine performance and economics. Deviations in site-specific wind speed distributions, up to 35 percent from design assumptions, contribute to unexpected dynamic loads, accelerate wear, and increase the risk of unplanned maintenance [3]. For drivetrain components such as bearings and gears, these stresses account for up to 70 percent and 26 percent of gearbox failures, respectively [3]. The result is an industry-wide challenge where drivetrain reliability remains a critical bottleneck, limiting operational efficiency and cost-effectiveness.

These limitations underscore the need for a paradigm shift in drivetrain load monitoring technologies. A solution that combines cost-effectiveness with real-time monitoring capabilities without the constraints of traditional systems could significantly enhance turbine reliability, reduce downtime, and enable proactive maintenance strategies. Such a solution must be robust, scalable, and capable of addressing the specific operational challenges wind farm operators face across varied environmental conditions.

Introducing AI-Driven Virtual Sensing

To address the limitations of traditional drivetrain monitoring methods, AI-driven virtual sensing technology offers a transformative approach by combining a static sensor setup with advanced machine learning models [1]. Unlike conventional systems, which rely on costly rotating sensors, this solution uses data from strategically placed sensors on non-rotating drivetrain components to estimate drivetrain loads accurately and in real time. The result is a scalable, cost-effective monitoring system that overcomes the barriers of traditional methods while enhancing turbine reliability.

The foundation of this technology lies in leveraging off-the-shelf sensors to collect data on drivetrain strains, which are then analyzed using machine learning algorithms trained on extensive test rig data. Validation of this system on the 4 MW wind turbine drivetrain test rig at the Center for Wind Power Drives in Aachen demonstrated its ability to estimate loads across multiple degrees of freedom [1]. For instance, torque estimation achieved a mean relative error of less than 1 percent of the rated torque, providing a high level of precision without the need for rotating components [1].

This approach eliminates reliance on complex hardware and enhances predictive capabilities. By providing continuous insights into drivetrain behavior under dynamic 6-DOF loading conditions, the technology enables operators to anticipate and address potential issues before they result in costly failures [1, 3]. For example, it allows for accurate differentiation of load profiles based on site-specific wind conditions, addressing a major challenge highlighted in traditional monitoring systems [3, 4].

Furthermore, this solution‘s modular design ensures adaptability across different turbine configurations and environmental conditions, making it applicable not only to new installations but also to retrofitting existing turbines. This flexibility ensures operators can adopt the technology with minimal disruption, benefiting from improved reliability and reduced operational costs regardless of turbine age or type.

Technical Capabilities

The AI-driven virtual sensing solution has been rigorously validated for its ability to monitor drivetrain loads accurately under simulated real-world conditions. This validation was conducted using the 4 MW wind turbine drivetrain test rig at the Center for Wind Power Drives in Aachen, a facility designed to replicate operational scenarios with high fidelity. These controlled yet dynamic loading conditions demonstrated the system‘s capability to estimate torque with a mean relative error of less than 1 percent of the rated torque, emphasizing its precision in capturing critical drivetrain loads [1].

The technology‘s strength lies in its ability to estimate loads across multiple degrees of freedom – such as torque and bending moments – using static sensors. This eliminates the need for rotating sensors, which are traditionally expensive, prone to failure, and challenging to maintain, particularly in offshore installations. Such precise load monitoring enables early identification of potential failure points and operational inefficiencies, which allows for proactive interventions to extend the lifecycle of drivetrain components [1, 3, 4].

Load monitoring enhances turbine operations by aligning them more effectively with site-specific conditions. For instance, turbines in high-turbulence regions often experience yaw misalignment-induced loads that accelerate drivetrain wear. Virtual sensing can quantify these loads in real time, enabling operators to optimize control strategies and balance energy production with component longevity [1, 4].

A notable insight from the research is the potential of continuous load monitoring to differentiate between degradation states among turbines, even those operating under identical environmental conditions. In one study, three turbines with the same design and location showed varying levels of drivetrain degradation, mainly due to site-specific dynamic loads that traditional monitoring approaches failed to capture [3]. This underscores the importance of advanced, real-time monitoring technologies such as virtual sensing, which leverage site-specific data to provide actionable insights for operation and maintenance.

By enabling detailed load analysis and addressing the limitations of conventional methods, AI-driven virtual sensing offers a transformative approach to drivetrain monitoring. It enhances reliability and supports proactive maintenance strategies, which allows for more cost-effective and sustainable turbine operations.

Implications for the Industry

AI-driven virtual sensing technology has the potential to transform the wind energy industry by addressing longstanding challenges in drivetrain monitoring, maintenance, and reliability. Drivetrain failures, particularly in offshore wind turbines, are among the most costly issues operators face, contributing significantly to operational and maintenance (O&M) costs [2]. Traditional CMS provides limited insights into drivetrain loads, focusing on detecting damage rather than predicting and preventing it [1, 3].

By enabling real-time load monitoring, AI-driven virtual sensing supports a shift toward predictive maintenance strategies. For example, drivetrain components such as bearings and gears – which collectively account for nearly all gearbox failures – can be monitored for early signs of critical wear based on actual operational loads [3]. This proactive approach reduces unplanned downtimes, allowing operators to plan interventions strategically and avoid costly reactive maintenance. Maintenance savings are particularly critical in offshore environments, where logistical challenges amplify repair costs [2, 3].

The environmental implications are equally significant. By prolonging the operational life of drivetrain components and reducing the need for replacements, virtual sensing minimizes the carbon footprint associated with manufacturing, transporting, and disposing of turbine parts. Additionally, improved reliability and fewer unplanned downtimes contribute to more consistent energy production, supporting the broader goal of sustainable and cost-effective renewable energy generation [3].

In summary, AI-driven virtual sensing delivers tangible benefits across operational, economic, and environmental dimensions. By addressing critical gaps in drivetrain monitoring, this technology offers wind farm operators a practical, scalable solution to enhance turbine reliability, reduce costs, and support the global transition to renewable energy.

Outlook

The potential of AI-driven virtual sensing extends beyond wind energy. Future research will explore its integration with IoT systems, applications in other renewable energy sectors, and advancements in machine learning models to enhance robustness and accuracy [1]. This technology will play a central role in developing sustainable energy systems by continuing to innovate.

Conclusion

AI-driven virtual sensing represents a transformative step forward in drivetrain load monitoring for wind turbines. By leveraging static sensor setups and advanced machine learning, this technology addresses critical gaps in traditional monitoring methods, offering real-time insights into drivetrain behavior with proven accuracy. Validated on the 4 MW test rig at the RWTH Aachen University, it demonstrated the ability to estimate torque with a mean relative error below 1 percent of the rated torque, highlighting its precision and practicality.

Beyond its technical capabilities, the solution empowers operators to enhance turbine reliability, reduce unplanned downtimes, and optimize maintenance strategies. Enabling proactive, data-driven decisions improves operational efficiency and contributes to the broader goals of sustainability and cost-effective renewable energy generation.

As the wind energy sector evolves, technologies like virtual sensing will be essential in addressing challenges tied to larger, more complex turbines and site-specific dynamic loads. With its scalability and adaptability, this solution is well-positioned to drive the next generation of monitoring systems, ensuring a more reliable and sustainable future for wind energy.

Potentials of AI-Driven Virtual Sensing

AI-driven virtual sensing leverages static sensors and machine learning to monitor drivetrain loads, improving turbine reliability and reducing operational costs. This scalable approach provides significant benefits for onshore installations by optimizing operations and reducing unplanned interventions. It is also particularly valuable for offshore wind farms, where maintenance logistics are complex and costly.

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Abstract

KI-gesteuerte Lasterkennung für den Betrieb von Windkraftanlagen – Kostengünstige Lösungen für die Zuverlässigkeit von Turbinen. Die Überwachung der Antriebsstranglasten ist für den zuverlässigen Betrieb von Windkraftanlagen wichtig, bisherige Methoden sind jedoch auf komplexe rotierende Sensoren angewiesen. Dieser Artikel hebt die industrielle Relevanz der KI-gesteuerten virtuellen Sensorik hervor, die einen statischen Sensoraufbau und mit realen Daten trainierte Modelle des Machine Learning einsetzt, um die Zuverlässigkeit der Anlagen zu optimieren, Kosten zu senken und die Vorhersehbarkeit des Betriebs zu verbessern.

Keywords

Wind Turbine Drivetrain, Load Monitoring, Virtual Sensing, Machine Learning, Operations and Maintenance, Reliability

Schlüsselwörter

Windenergieanlagentriebstrang, Lastüberwachung, Virtuelle Sensorik, Maschinelles Lernen, Betrieb und Wartung, Zuverlässigkeit

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