Developing a Main Bearing Load Estimation Model to Predict Reliability of Next-Generation Offshore Wind Turbines

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Abstract

Main bearings in wind turbines are a critical failure component with expensive maintenance costs. These issues exist in a market where offshore wind turbines are accelerating in deployment, growing in capacity and size, and gradually adopting direct-drive systems. Main bearing reliability and cost issues are exacerbated as component mass and loads increase due to these industry trends. Previous studies often employ high-fidelity, computationally expensive analysis tools and group the main bearings in larger systems. In this study, a fast, component-focused main bearing load estimation model is developed. The model employs wind turbine simulations data and reference wind turbine parameters which enables a computationally efficient reliability estimation method for main bearings of wind turbines. I validate this model to calculate fatigue load and life of main bearing in offshore direct-drive reference wind turbines. This work has the potential to expand existing wind farm modelling and enable researchers to consider main bearing reliability by integrating this open-source model. Through the product developed in this study, it is the ultimate goal to improve wind turbine reliability, reduce lifetime costs, and allow greater accessibility in order to make offshore wind more competitive in the current energy market.

I. INTRODUCTION

Global wind energy deployment has grown by nearly 300% in the past decade to a cumulative installed capacity of 650 GW worldwide.[?] The rapid growth of the wind energy market has been partially enabled by the increasing power generation capacity and size of wind turbines, two directly correlated factors. In 2019, the average turbine capacity for offshore wind energy was 6 MW with a rotor diameter of 100 meters, however, projections show these numbers increasing to 11 MW and 200 meter, respectively, by 2025.[?] The offshore wind energy sector is a relatively new and growing market and has recently reached a global capacity of 29.1 GW.[?] As of 2019, over 6.4 GW of offshore projects are currently in the planning pipeline in the US, with projected growth expected to increase as west coast installations begin. [?]

Offshore locations pose new opportunities as well as engineering challenges. As wind turbine move offshore, they can be designed to be significantly larger with greater capacities because space availability and visual impact are of lesser concern in offshore settings. In addition, wind speeds are higher and more consistent offshore, leading to annual yields of up to 50% more electricity than onshore wind turbines of equal capacity and type.[?] However, challenges such as component failure and the associated operations and maintenance (O&M) costs are only exacerbated by the growing size of turbines. O&M costs is reported to be as a high as 35% of the total lifetime cost of offshore wind project. This is largely caused by reduced accessibility in varying ocean conditions as well as the specialized vessels, technicians, and parts required for frequent maintenance and repair.[?] Offshore wind turbines experience significantly higher failure rates than onshore wind projects, reported to be caused by higher wind speeds and larger capacity of turbines offshore.[?] Wind turbine reliability remains a major roadblock in accelerating offshore wind deployment.

This study analyzes specifically wind turbine main bearings, a critical failure component. The main bearings in wind turbines employ rolling elements to constrain relative motion between the turret and main shaft, allowing the turbine rotor to rotate with minimal friction. This component interacts with both the rotor and drivetrain, and thus is affected by the aerodynamic and torque loads from the wind field as well as the non-torque load from the drivetrain.[?] Main bearings are a high-risk component, with studies that report failure rates at nearly 30% over a 20-year lifetime.[?] Main bearings have shown increasing evidence of failure, with many turbine bearings failing to survive beyond 6 years.[?] Wind turbines that employ spherical roller bearings (SRB) are especially susceptible to micro pitting, single piece cage failure, roller edge loading, as well as debris damage.[?] These failure modes inevitably compromise the entire system operation, leading to expensive downtime and repairs. For reference, the presence of micro-pitting on the main bearing rollers can result in repair costs of 150k to 300k USD 2013.[?] The leading failure modes of the main shaft all involve the fatigue or wear of raceways and rollers, primarily due to microgeometry, local overload, and lack of lubrication. [?] Fatigue is one of the most prominent failure modes for the main bearings, causing plastic deformation and fatigue cracking, which often triggers other failure mechanisms.[?,?] Therefore, reducing component failure and improving reliability is essential in reducing lifetime costs and making offshore wind energy more competitive in the energy market.

A preventative and predictive tool critical in accomplishing this is modelling. Larger, heavier turbine components lead to increased loads and stresses in the system, increasing the importance of component modelling and simulations for wind turbine analysis.[?,?] Wind turbines are subjected to fluctuating loads and vibrations which propagate throughout the structure and drivetrain.[?] As highlighted by Li et al., these dynamic loads are currently analyzed using the following approaches: (1) pure torsional rigid models, (2) multi-degree-of-freedom (DOF) rigid models, (3) flexible multibody models. [?] These approaches vary in complexity, fidelity, and computational expense. Often, torsional rigid multibody models, which do not account for lateral loads in the drivetrain, are not sufficient to produce realistic results. On the other hand, flexural dynamic models which consider the elasticity of each gear, carrier, and housing in the drivetrain, are computationally expensive.[?] Main bearing modelling approaches include using the Hertzian elastic contact theory, finite element (FE) models, and multi-body simulations (MBS).[?] Publication focusing on main bearing modelling of wind turbines are limited, however. Numerous prominent studies such as Li et al., Helsen et al., and Scheu et al. in the past have overlooked the main bearing or included it under larger systems such as the drivetrain or main shaft in modelling and failure analysis.[?,?,?]

The study develops a computationally inexpensive, component focused main bearing model using mid-fidelity data to predict fatigue loads and life. Offshore wind turbines are growing in popularity and capacity while the main bearing remains a component with a high failure rate and maintenance cost. It is currently unclear how the degradation and reliability of main bearings are affected by the trends of the industry, especially when looking at direct-drive systems. Additionally, component analysis on a wind farm scale calls for a computationally inexpensive mode to estimate main bearing loads. To address these gaps, this study establishes an open-source, fast analytical model for the main bearings of direct drive wind turbines. This model calls for reference wind turbine (RWT) design parameters which are gathered and organized in the methods section. Additionally, main bearing specification are either gathered from previous reports or established through design for each RWT. Using the analytical model and parameters, the L10 life is calculated for the RWTs with simulation data inputs. The flow of data parameters through each model is shown in Figure **??**. Section C. will describe the validation method used to verify the analytical model. Developed as part of the Reliability-Based Layout Optimization software,[?] this work enables the consideration of main bearing loads and reliability in layout optimization of wind plants for three RWTs. The product of this study is the accumulation of drivetrain and main bearing parameters of previous RWTs and a versatile tool for main bearing modelling. Through this work, it is the goal to enable researchers to integrate this tool which may ultimately improve main bearing reliability, reduce wind turbine life time cost, and accelerate offshore wind deployment in order to reduce carbon emissions.

II. Methods

A. Reference Wind Turbines

1. IEA 15 MW Offshore Reference Wind Turbine

2. IEA 10 MW Offshore Reference Wind Turbine

3. Modified Direct-Drive 5 MW Reference Wind Turbine

B. Model Formulation

C. Model Validation

D. L_{10} Formulation

III. Results and Discussion

A. Bearing Loads and Validation

B. Model Limitations and Future Works

IV. Conclusion