

Improving Wind Turbine Gearbox Reliability

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Summary

This paper describes a new research and development initiative to improve gearbox reliability in wind turbines begun at the National Renewable Energy Laboratory (NREL) in Golden, Colorado, USA. The approach involves a collaboration of NREL staff, expert consultants, and partners from the wind energy industry who have an interest in improving gearbox reliability. The membership of this collaborative is still growing as the project becomes more defined, but the goal is to include representatives ranging from the operators, owners, wind turbine manufacturers, gearbox manufacturers, bearing manufacturers, consultants, and lubrication industries. The project is envisioned to be a multi-year comprehensive testing and analysis effort. This will include complementary laboratory and field testing on a 600 to 750-kW turbine and gearbox of a configuration that exhibits reliability problems common to a broad population of turbines. The project will target deficiencies in the design process that are contributing to substantial shortfalls in service life for most designs. New design-analysis tools will be developed to model the test configuration in detail. This will include using multi-body dynamic analysis to model wind turbine loading, coupled to internal loading and deformations of the gearbox. Intellectual property conflicts will be minimized by maintaining a test configuration that does not replicate any specific manufacturer's wind turbine model precisely, but represents a common configuration.

Background

The wind energy industry has experienced high gearbox failure rates from its inception [1]. Early wind turbine designs were fraught with fundamental gearbox design errors compounded by consistent under-estimation of the operating loads. The industry has learned from these problems over the past two decades with wind turbine manufacturers, gear designers, bearing manufacturers, consultants, and lubrication engineers all working together to improve load prediction, design, fabrication, and operation. This collaboration has resulted in internationally recognized gearbox wind turbine design standards [2]. Despite reasonable adherence to these accepted design practices, wind turbine gearboxes have yet to achieve their design life goals of twenty years, with most systems requiring significant repair or overhaul well before the intended life is reached [3,4,5]. Since gearboxes are one of the most expensive components of the wind turbine system, the higher-than-expected failure rates are adding to the cost of wind energy. In addition, the future uncertainty of gearbox life expectancy is contributing to wind turbine price escalation. Turbine manufacturers add large contingencies to the sales price to cover the warranty risk due to the possibility of premature gearbox failures. In addition, owners and operators build contingency funds into the project financing and income expectations for problems that may show up after the warranty expires. To help bring the cost of wind energy back to a decreasing trajectory, a significant increase in long-term gearbox reliability needs to be demonstrated.

In response to design deficiencies, modification and redesign of existing turbines is a continual process in current production units, but it is difficult to validate the effectiveness of the modifications in a timely manner to assure that multiple units with unsatisfactory "solutions" are not deployed. Presently, gear manufacturers introduce modifications to new models, replacing a deficient component with a re-engineered one that is

thought to deliver higher performance. To test these new designs, the re-engineered gearboxes are installed and a field evaluation process begins. This approach may eventually lead to the reliability goals needed, but it may take many years to develop the needed confidence in a solution, and reduce the uncertainty to a level where it will reduce turbine costs. By that time, the wind turbine industry may have moved to larger turbines or different drivetrain arrangements that could invalidate these solutions. Moreover, the fundamental failure mechanisms of the original problem may never be understood, making it easier for design unknowns to be inadvertently propagated into the next generation of machines.

This paper summarizes a long-term NREL/DOE project to explore options to accelerate improvements in wind turbine gearbox reliability by addressing the problems directly within the design process. In the execution of this program, our intentions are to improve the accuracy of dynamic gearbox testing to assess gearbox and drivetrain options, problems, and solutions under simulated field conditions. The project will evaluate the wide range of possible load events that comprise the design load spectrum [6], and how critical design-load cases [7] may translate into unintended bearing and gear responses such as misalignment, bearing slip, and axial motion.

NREL has made a commitment to address gearbox reliability as a major part of its research agenda, and plans to engage a wide range of stakeholders including researchers, consultants, bearing manufacturers, gearbox manufacturers, wind turbine manufacturers, and wind turbine owner/operators to form a gearbox reliability collaborative (GRC). The collaborative will address major gearbox issues with the common goal of increasing overall reliability of wind turbines. The approach will involve three major technical efforts which include field testing, dynamometer testing, and drivetrain analysis. These elements make up a comprehensive strategy that will address the true nature of the problem and hopefully spark a spirit of cooperation that can lead to better gearboxes.

Observations on the Basic Problems

While it is premature to draw firm conclusions about the nature of these failures, some reasonable observations have been made to help narrow the course and scope of this project.

1. Most of the problems with the current fleet of wind turbine gearboxes are generic in nature, meaning that the problems are not specific to a single gear manufacturer or turbine model. Over the years, most wind turbine gearbox designs have converged to a similar architecture with only a few exceptions. Therefore, there is an opportunity to collaborate among the many stakeholders in the wind turbine gearbox supply chain to find root causes of failures and investigate solutions that may advance the collective understanding of the industry.
2. The preponderance of gearbox failures suggests that poor adherence to accepted gear industry practices, or otherwise poor workmanship, is NOT the primary source of failures. Of course, some failures have been directly attributed to quality issues, and further improvements in this area are not precluded from consideration, but we assume that manufacturers are capable of identifying and correcting quality control problems on their own if they choose to do so. Therefore, the target of this project will be the greater problem of identifying and correcting deficiencies in the design process that may be diminishing the life of the fleet.
3. Most gearbox failures do not begin as gear failures or gear-tooth design deficiencies. The observed failures appear to initiate at several specific bearing locations under certain applications, which may later advance into the gear teeth as bearing debris and excess clearances cause surface wear and misalignments. Anecdotally, field-failure assessments indicate that up to 10% of gearbox failures may be manufacturing anomalies and quality issues that are gear related, but this is not the primary source of the problem.
4. The majority of wind turbine gearbox failures appear to initiate in the bearings. These failures are occurring in spite of the fact that most gearboxes have been designed and developed using the best bearing-design practices available. Therefore, the initial focus of this project will be on discovering weaknesses in wind turbine gearbox bearing applications and deficiencies in the design process.

5. Furthermore, we believe that the problems that manifested themselves in the earlier 500-kW to 1000-kW sizes five to ten years ago still exist in many of the larger 1 to 2 MW gearboxes being built today with the same architecture. As such, it is likely that lessons learned in solving problems on the smaller scale can be applied directly to future wind turbines at a larger scale, but with less cost.

Using these observations to help bound the problem, we reason that the accepted design practices that are applied successfully throughout other industrial bearing applications must be deficient when applied to wind turbine gearboxes. This characterization is based primarily on anecdotal field-failure data, and the experience of gear and bearing experts who have studied the problems for many years. Unfortunately, the available analytical methods to assess design life in typical gearbox designs are not accurate enough to shed much light on this problem, so much of the investigation must be conducted empirically.

A major factor contributing to the complexity of the problem is that much of the bearing design-life assessment process is proprietary to the bearing manufacturers. Gearbox designers, working with the bearing manufacturers, initially select the bearing for a particular location and determine the specifications for rating. The bearing manufacturer then conducts a fatigue life rating analysis to determine if the correct bearing has been selected for the specific application and location. Generally, a high degree of faith is required to accept the outcome of this analysis because it is done with little transparency. Even though bearing manufacturers claim adherence to international bearing-rating standards (ISO 281:2007 [8]), each manufacturer uses its internally developed design codes that have the potential to introduce significant differences that can affect actual calculated bearing life without revealing the details to customers. A new code is needed in the public domain that will give the industry a common method for due diligence in bearing design [9].

Moreover, since the bearing manufacturers do not have broad or intimate knowledge of gearbox system loads and responses that may be contributing to unpredicted bearing behavior beyond the bearing mounting location such as housing deformations, they are not capable of making valid root-cause analyses on their own. A broader collaboration of the various stakeholders, each of whom holds a piece of the answer, is clearly needed.

Gearbox Reliability Collaborative

Many of the gearbox problems described above may be the direct result of institutional barriers that hinder communication and feedback during the design, operation, and maintenance of turbines. In isolation, it is very difficult for single entities in the supply chain to find proper solutions. Hence, a collaborative is needed to bring together the various portions of the design process, and to share information needed to address the problems. This promises to be one of the more challenging parts of this project, as information sharing introduces perceived risk to the protection of intellectual property, which is guarded dearly by most companies. A goal of this project is to establish this cooperative framework while protecting the intellectual property rights of all parties. These concerns will be addressed through legal agreements with NREL, and will be further mitigated since the project does not focus on any manufacturer's specific design. The collaborative is operated by NREL staff and expert consultants hired by NREL to guarantee privacy of commercially sensitive information and data. In addition, a goal of the collaborative is to engage key representatives of the supply chain, including turbine owners, operators, gearbox manufacturers, bearing manufacturers, lubrication companies, and wind turbine manufacturers. Each party holds information and experience that is needed to guide the project, supply the components, and interpret results of the test. The collaborative partners will benefit by having input throughout the testing setup and execution, and will have access to data within the agreements established by the cooperative. Results will be released by the GRC as agreed upon by its members.

Generic Wind Turbine Drivetrain Architecture

The selected configuration is comprised of a single main bearing upwind of the gearbox with rear non-locating support bearings inside the gearbox. Trunnion mounts on either side of the gearbox are used to attach it to a mainframe or bedplate, typically through elastomeric bushings used to dampen noise and vibrations. Torque reactions are resolved through the trunnion support assembly that is normally an integral part of the gear housing. The external geometry of this configuration is shown in Figure 1.

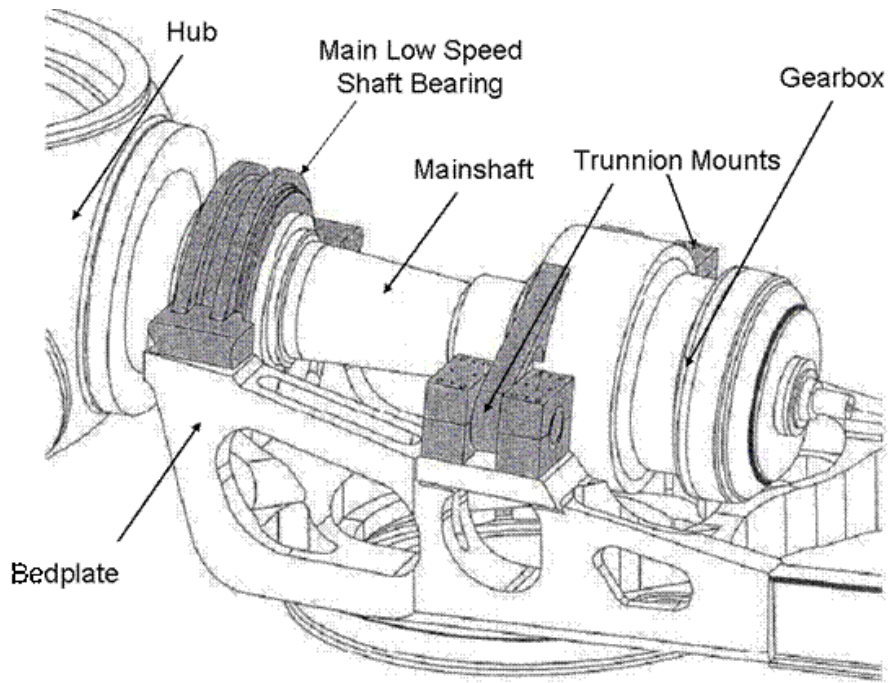


Figure 1 – Typical Wind Turbine Gearbox Mount [10]

The low speed stage of the gearbox is a planetary configuration with either spur or helical gears. The sun pinion drives a parallel intermediate shaft that in turn drives a high speed stage. Both the intermediate and high speed stages use helical gears. A generalized schematic of a typical wind turbine gearbox is shown in Figure 2.

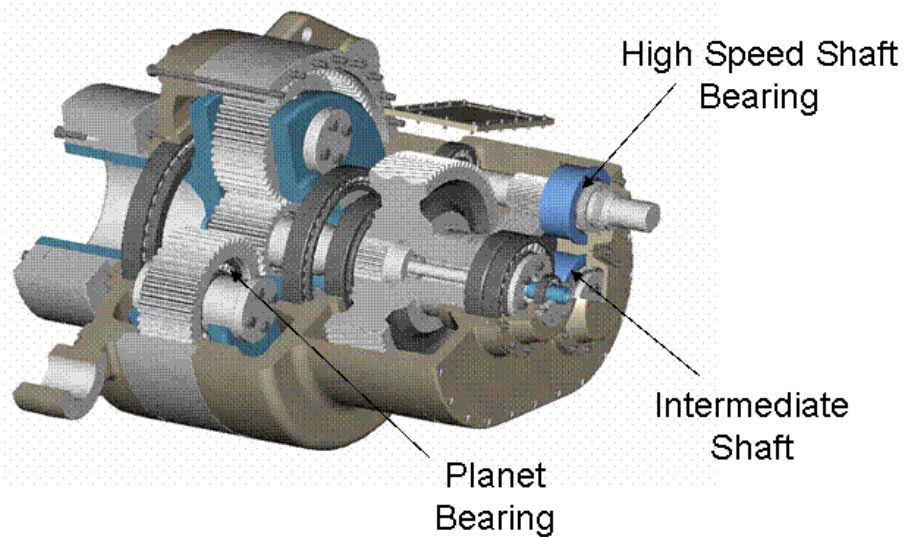


Figure 2 – Generalized Gearbox Schematic [11]

Critical bearing locations are defined as places that have exhibited a high percentage of application failures in spite of the use of best current design practices. In the generic configuration, there are three critical bearing locations that we have identified:

1. Planet bearings
2. Intermediate shaft-locating bearings
3. High-speed locating bearings

Each location has exhibited a relatively high degree of bearing failures with a relatively low dependence on machine size, machine make, or model.

A Three Point Plan

As previously mentioned, some aspects of the wind turbine, gearbox, and bearing design process are preventing gearboxes from reaching expected life. These deficiencies could be the result of many factors, including:

- the possibility that one or more critical design-load cases were not accounted for in the design load spectrum,
- that transfer of loads (both primary torque loads and non-torque loads) from the shaft and mounting reactions is occurring in a non-linear or unpredicted manner, or
- that components within the gearbox (especially the bearings) are not uniformly specified to deliver the same level of reliability.

Due to the complexity of this problem, a comprehensive approach that expands our existing base of knowledge and capabilities will be required. Under this project, NREL plans an integrated three-pronged approach of analysis, dynamometer testing, and field testing as shown in Figure 3.

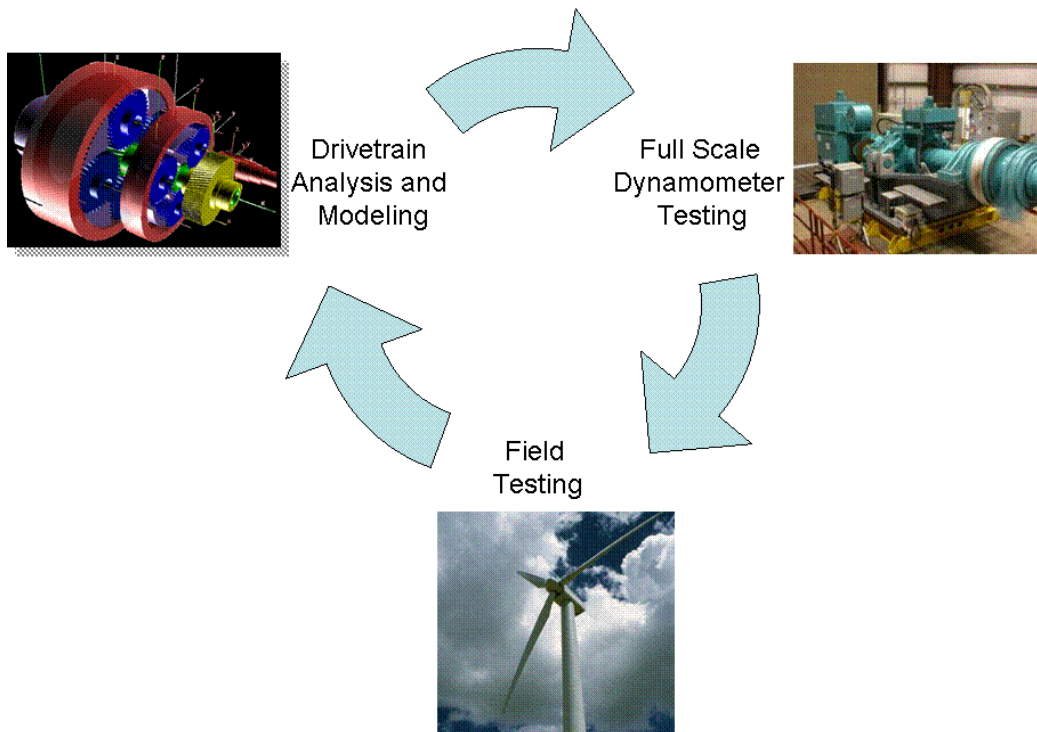


Figure 3 - Comprehensive Strategy to Investigate Wind Turbine Gearbox Reliability

Laboratory testing of a representative instrumented drivetrain in the NREL 2.5-MW dynamometer will be coordinated with parallel field tests on an identical instrumented drivetrain conducted at a nearby wind farm site. With the benefit of hindsight, the selected drivetrain will be upgraded prior to testing to current state-of-the-art to eliminate known design weaknesses and quality issues as best as possible. These upgrades may include different bearing types, cooling and filtration system upgrades, lubrication changes, and gear tooth modifications. The test specimens will therefore not be precise representations of any manufacturer's design. The laboratory and field measurements will be validated with dynamic analysis using an accurate structural-system model of the selected drivetrain.

The test will be based on a 600 to 750-kW wind turbine selected by a committee of expert gearbox consultants hired by NREL under the GRC. The exact details of the drivetrain to be tested and analyzed are confidential to the members of the GRC. Project success will be highly dependent on making the right measurements that correctly characterize the behavior of the critical bearings under various loading scenarios. Instruments will be developed and installed to capture data about significant loads, deflections, thermal effects, dynamic responses and events, and changes to the condition of the lubricant.

Critical loads measurements will include shaft bending and torque on the input shafts, but also measurements of how load sharing varies dynamically from one planet bearing to another. Similarly, measurements will be made to determine how the load is being shared between bearings axially along a single planet shaft. Displacement sensors to make continuous measurements will be installed internally, if possible, wherever gear tooth clearances or alignments of the gears might be affected. These locations may include bearing inner ring to outer ring alignments and clearances, shaft axial motions, bearing slip (inner or outer motions or bearing components), roller slipping or skidding, combined roller slip, relative motion of carrier to housing, sun pinion displacement relative to carrier, sun-pinion axial motion, housing stiffness, and displacement measurements of housing. We anticipate that certain locations will be difficult to access with standard instrumentation. Temperature measurements will be made at all critical bearing locations, including the inner rings, the outer rings, and planet bearings. Lubrication monitoring will include bulk sump temperature, cleanliness (e.g., particulate, ferrous, additive, and water), and filter debris. Laboratory analysis will be conducted frequently on all test specimens.

The test data will be analyzed and correlated to look for bearing behavior that is unexpected, non-linear, or is suspect under a wide range of input conditions. If this behavior can be correctly documented and understood, it may not be necessary to reproduce every type of bearing failure if subsequent analysis can demonstrate that certain abnormal behavior can result in loss of bearing life.

Dynamometer Testing

The National Renewable Energy Laboratory operates a 2.5-MW dynamometer test facility funded by the U.S. Department of Energy at its National Wind Technology Center in Golden, CO that is dedicated to the testing of wind turbine drive trains [12]. Since 1999, this facility has been in continuous operation providing testing services to prototype and production wind turbine drive trains up to 2 MW in size. NREL plans to use this facility and its support staff to conduct full-scale tests on the 750-kW drivetrain selected. A schematic of the facility is shown in Figure 4.

One of the benefits of using a full scale drive-train test facility is that the time to evaluate new configurations can be reduced by an order of magnitude or more (compared to field testing) since loading conditions can be repeated and accelerated as needed. Instrumentation is easier to install and maintain, and the results can often be observed first-hand from a safe vantage point.

One limitation is that the prescribed loading in the test facility is currently capable of applying only low-speed shaft torque with a very simple single-point transverse load (up to 100 kips) that might represent shaft bending load due to gravity, but not in a dynamic situation. Plans are underway to upgrade the facility to enable more complex dynamic-load combinations, including low-speed shaft bending in two directions, shear loading, as well as a reversing axial thrust component. This additional loading capability will enable better simulation of the actual field conditions in real-time operation.

Another potential problem is that the transfer function between external shaft loading and internal gearbox responses may not be the same in the dynamometer as it is on the turbine under field operation due to differences in mounting stiffness or component inertia. Initial testing will examine and characterize these effects to establish a valid correlation between field tests and laboratory results. Of critical importance will be

showing how anomalous events such as non-linear bearing responses might be contributing to the premature failures.

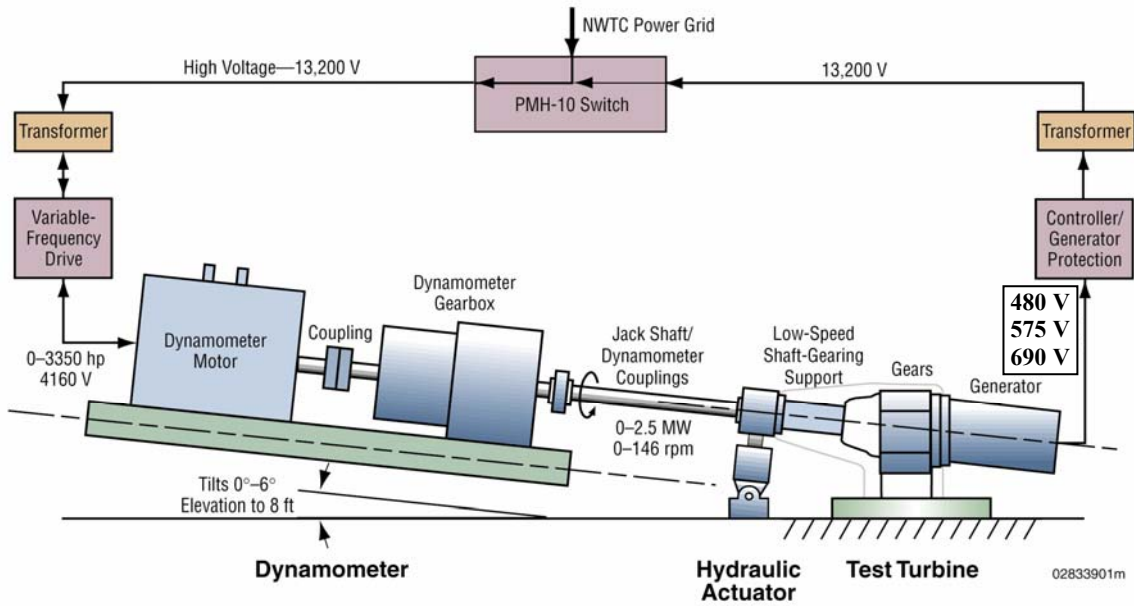


Figure 4 – Schematic of NREL 2.5 MW Dynamometer Test Facility



Figure 5 – Ponnequin Windfarm Test Site – Northern Colorado – USA [13]

Field Testing

Field testing will be conducted at the Ponnequin windfarm shown in Figure 5, which is owned and operated by Xcel Energy.

Field testing will be conducted on a wind turbine with the identical gearbox configuration as the drive train that is tested in the NREL dynamometer. The primary purpose of the field test is to measure the loading characteristics of the turbine under field operation, and record all the design load cases and their corresponding reactions and responses that are generated at the critical bearing locations identified above.

These measured field loads will be required to correlate the measured responses in the dynamometer test facility generated under the same loading. Due to difference between the stiffness of the drivetrain mounting in the dynamometer, system inertias, and other configuration modifications, the dynamometer responses may need to be tuned to match field conditions.

Drivetrain Analysis

Drivetrain analysis tools will be developed to model the internal gear and bearing load reactions, and internal displacements and motion under simulated field conditions. Similar analyses have been performed to investigate the multi-body dynamics of gears and shafts, but bearing behavior was not considered [14].

The analysis will use multi-body dynamic analysis to relate the global rotor loads calculated using the FAST wind turbine code to the subcomponent level of the inside of the gearbox [15]. Accurate geometry and stiffness properties for each of the gearbox elements (including gear housing, shafts, bearings, and gears) will be represented using SimPack™ software [16]. A preliminary model is shown in Figure 6.

Commercially available gear design, analysis, and rating software (GEARCALC [17], RIKOR [18], LVR [19]) will be used to assess the gear tooth loads, and establish load capacity limits for the “as built” gearbox. The model will be tuned using inputs from dynamic analysis, field test results, and dynamometer testing through an iterative process. A similar approach will be utilized with gear rating codes by working with a bearing design partner (using their in-house codes) and in validating public domain bearing-rating software now under development.

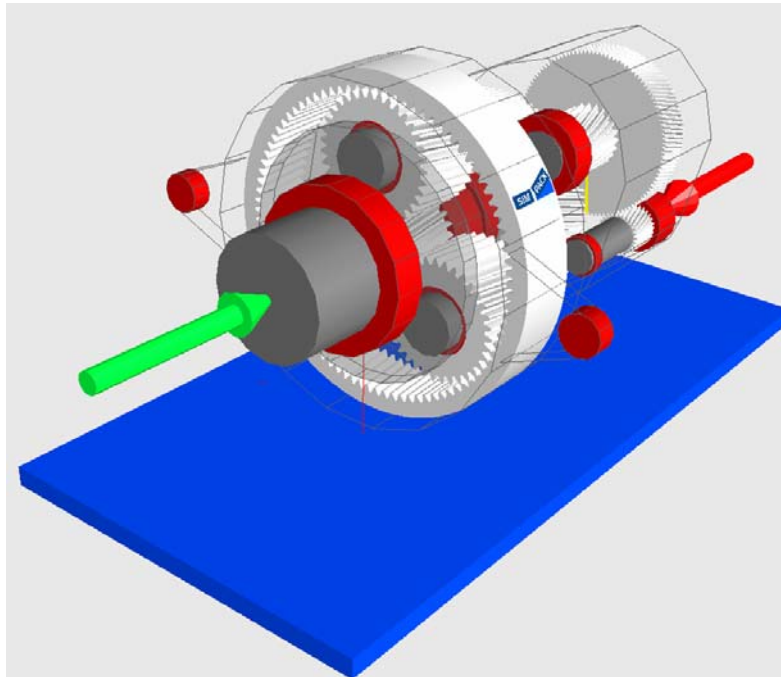


Figure 6 - Preliminary Model of Gearbox using SimPack™ software

By building this modeling capability, future designers will benefit by having a validated design process that is capable of developing and identifying critical load cases for gearbox design. Predicting gearbox load responses to specified load conditions that can be measured in the field will also be modeled. The validated model will be useful in extrapolating to extreme or rare-event load cases that may not be easy to capture in

the field or apply in the dynamometer test stand. Drive train solutions can be simulated in the validated model before implementing them in the laboratory or field, which will reduce the design-loop cycle time and allow more solutions to be assessed while building confidence in the proposed solution. We anticipate that ultimately, the combined testing and analysis efforts can help refine the design process and contribute significantly to better practices and improved system reliability.

Conclusions

The wind industry has reached a point where design practices for gearboxes do not result in sufficient life, and institutional barriers are hindering forward progress. A new approach is needed to overcome these barriers and accelerate the development of more robust gearbox designs. The Gearbox Reliability Collaborative initiated at NREL provides a fresh approach toward better gearboxes that combines the resources of key members of the supply chain to investigate design-level root causes of field problems and solutions that will lead to higher gearbox reliability.

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