AN INVESTIGATION OF CONTROL STRATEGIES ON GEARBOX DAMAGE

Christopher Halse*, Zhiwei Zhang*, Ashley R. Crowther*, Sergio Dominguez†, Arek Dutka†, William Leithead†‡

*Romax Technology Ltd., †MLS, ‡ University of Strathclyde

Abstract:

The impact of control on structural elements such as tower and blades have been thoroughly researched and the validity of analysis methods based on aeroelastic simulations is widely accepted. The implications on gearbox wear for various control strategies is less studied. Using RomaxDesigner for gearbox analysis, MLS and Romax have carried out an investigation where the impact of different control strategies on wear is assessed. The best measures accounting for gearbox damage are described and the different control strategies and their impact on the gearbox are detailed.

1. Objectives

The analysis of loads and fatigue on the structural elements of the wind turbine are required for certification and are an essential part of the design process. In the case of the gearbox the typical practice for turbine control simulations is to model with a gain element where an equivalent stiffness, damping and inertia represents the low and high speed shafts, the gears and the generator rotor. The models predict the global dynamic loading but do not calculate gearbox component fatigue. In this work we take advantage of detailed gearbox models developed by Romax to undertake a more thorough analysis using the system response predictions of the typical loads imposed by changing wind conditions. The method leads to a better understanding of how to utilize control to improve gearbox reliability. The synergy with MLS control design is achieved by first using dynamic models to investigate the impact of the control strategy on the loads generated within the drivetrain elements. For illustration, six different controller designs with different properties are implemented and aeroelastic simulations carried out. The calculated loads are then applied to a detailed gearbox model in order to predict the fatigue damage. The objective is to allow a method for designers to determine the influence of the control strategy on the predicted life of components in the gearbox.

2. Experiment setup

The controllers are implemented as Simulink block diagrams and applied as the external controllers for aeroelastic simulations within GH Bladed. The interface has been developed by MLS and allows for direct connection between the two computer software packages. This approach minimises the time spent on the controller coding; no c-code is needed and the implementation is made using the graphical programming elements of Simulink.

Figure 1 shows the MLS Gateway with a Simulink controller and Figure 2 the external controller within GH Bladed that communicates with the MLS Gateway. The six controllers are designed as follows. Controllers 1 and 2 are tuned with the aim of achieving different bandwidths. Controller 2 achieves slightly wider bandwidth at the expense of narrower stability margins. These controllers both incorporate drivetrain damping filters. Controller number 3 has no drivetrain filter and consequently the bandwidth of the loop had to be reduced to achieve required stability margins. Controllers 4, 5 and 6 use the generator reaction torque to achieve some of the control objectives in above rated operation. This suggests that as a consequence the drive train and the gearbox may be subject to increased loading. For the controllers the analysis of the gearbox damage is of high importance. Controller 4 uses the pitch angle for actuation for frequencies below 0.7 rad/s in above rated operation. For higher controller command frequencies the generator torque is utilized. Consequently, this strategy will reduce the tower fatigue since the pitch activity at a natural frequency of the tower might result in the excitation of that mode and increased tower fatigue. Controller 5 is designed to be more selective. It utilizes generator reaction torque for above-rated control only for control signals at the tower natural frequency. This in turn minimises usage of the reaction torque signal and is likely to reduce loading on the drivetrain. Controller 6 is designed to control power output instead of the generator speed. Above rated the generator reaction torque is utilised only at the tower frequency.

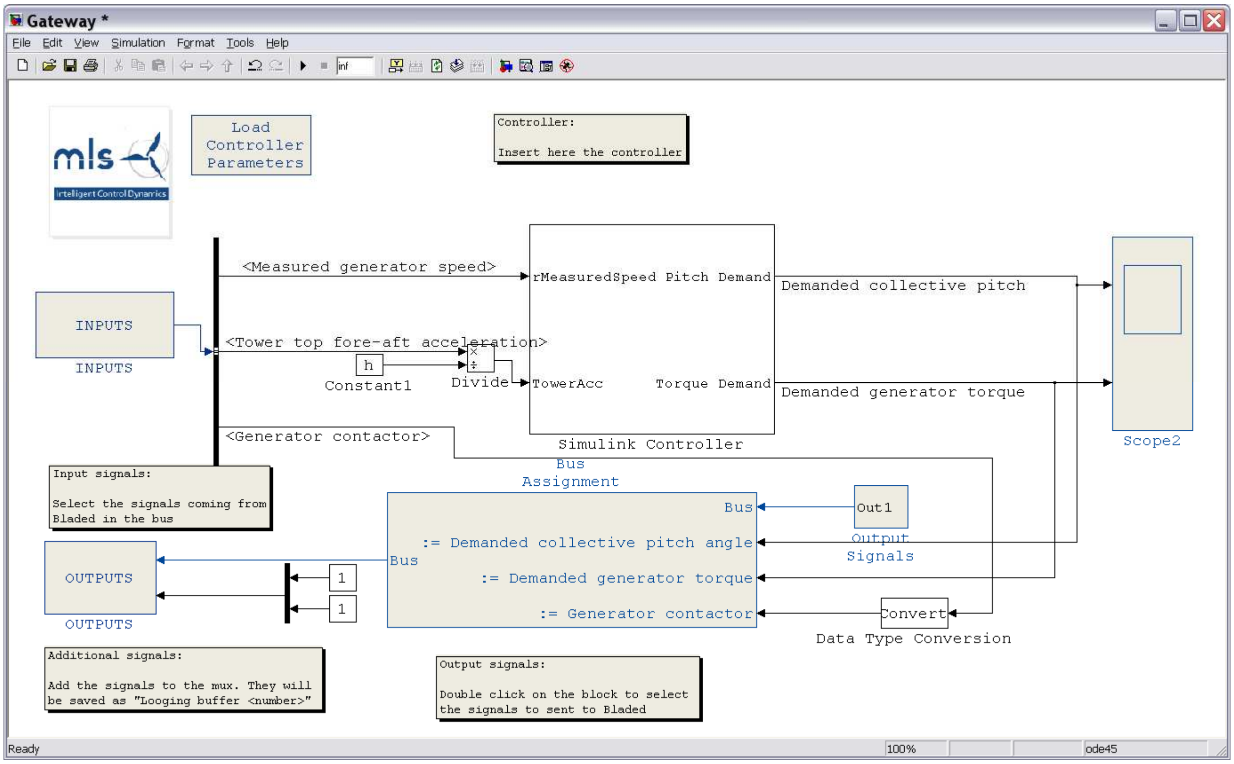


Figure 1: MLS Gateway with a Simulink controller

The analysis described in this paper is aimed at evaluating the impact of an increase in activity of the generator reaction torque on the gearbox damage. The results of damage analysis are intended to give a relative measure of the increase in loads. Controllers 1 and 2 are intended to give a baseline load measure and the impact of the advanced control technique that aims at minimising tower fatigue is assessed.

Results from the simulation of the wind turbine power production cases are collated for each of the six controllers. Each set of results consists of 22 datasets of ten minutes. The torque and speed results for each controller are converted into a load distribution for the input torque. These are histograms that describe the distribution of the cycles over the torque range, as shown in Figure 3.

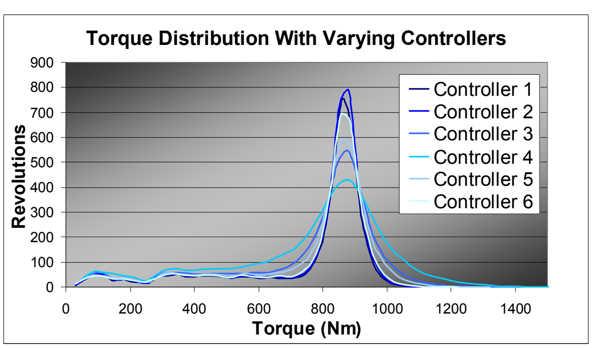


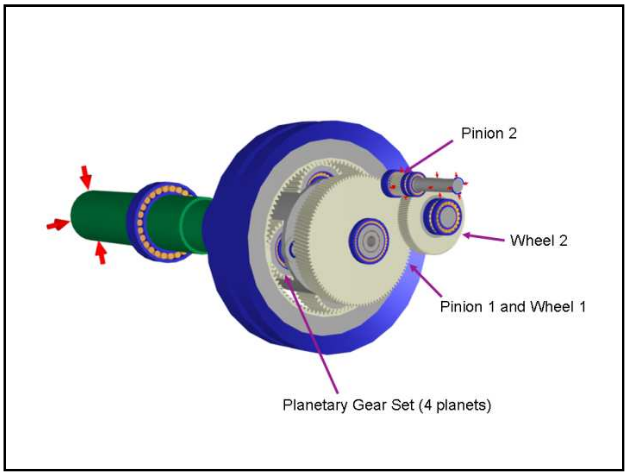
Figure 3: Torque Distribution with Varying Controllers

This is a basic representation of the loads on the wind turbine gearbox intended to be sufficient for comparison purposes. A more realistic load distribution would take into account many more simulation cases including, for example, generator short-circuit events and extreme gust events. For some drivetrain arrangements (specifically the mounting of the gearbox and mainshaft) the non-torsional loading should be accounted for in design calculations.

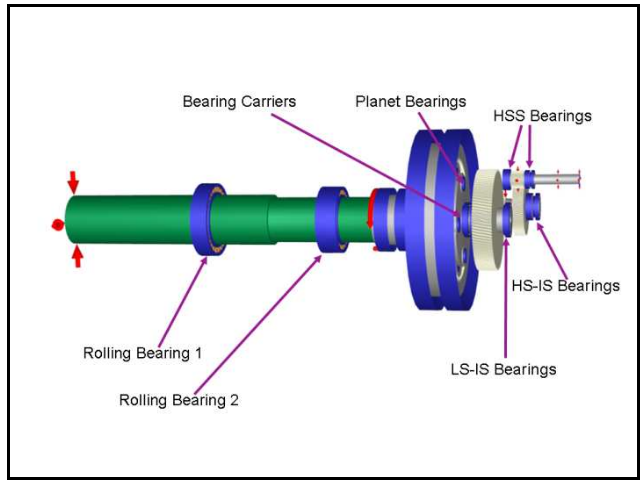
3. Gearbox Damage Analysis

For the purpose of this illustrative example a RomaxDesigner model [1] (Figure 4) has been built for a generic 1500kW wind turbine gearbox. The gearbox features one planetary gear set, with 4 planets and two parallel helical gear stages.

The RomaxDesigner model includes beam element representations of the shafts, gear meshes with stiffness determined according to [2] (which is a basic option for calculation available in the software) and the Romax proprietary nonlinear fully coupled bearing model. For drivetrain design projects more detailed models are typically built with flexible representations of housings, bedplates and planet carriers. The model is fully integrated with calculations for gear damage (according to [2]) and bearing damage (using a method derived from [3]). The calculation accurately predicts system misalignment and thus the face load factors for gears and the load zone factors for bearings can be calculated. Figures 6-8 provide the results for the gear and bearing damage for each of the six load distributions as produced by the controller simulations.



(a)



(b)

Figure 4: RomaxDesigner Model for a Generic 1500kW Wind Turbine Drivetrain with Elements Labelled: (a) Gear Sets; (b) Bearings

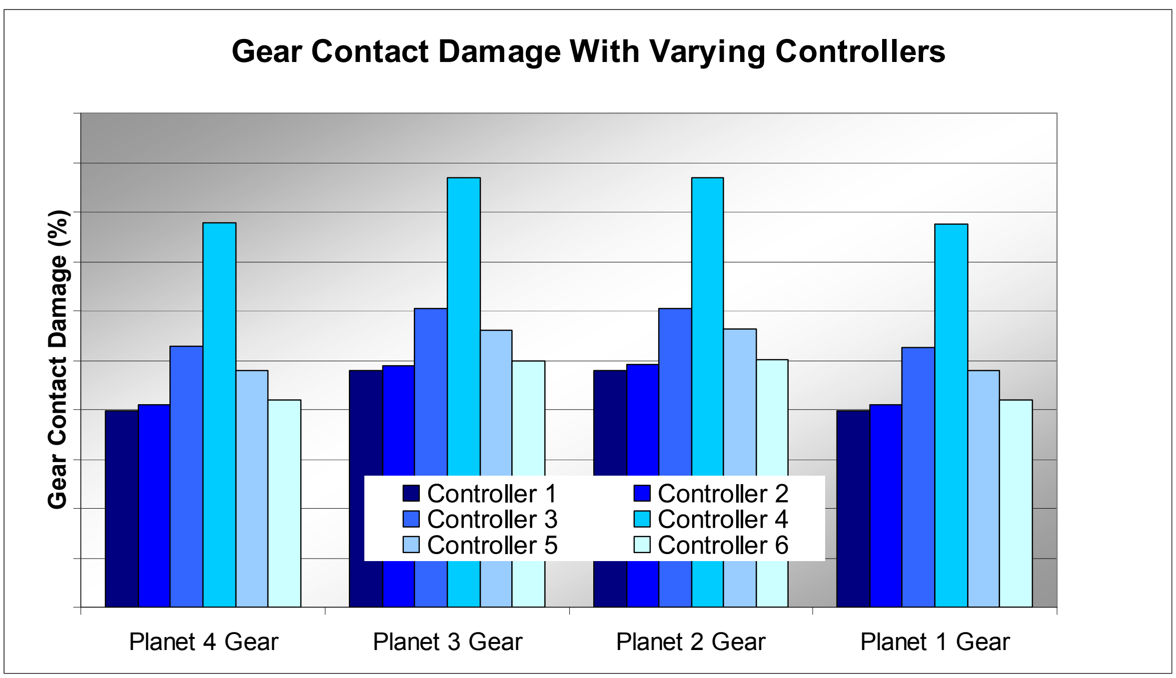


Figure 5: Gear Contact Damage with Varying Controllers

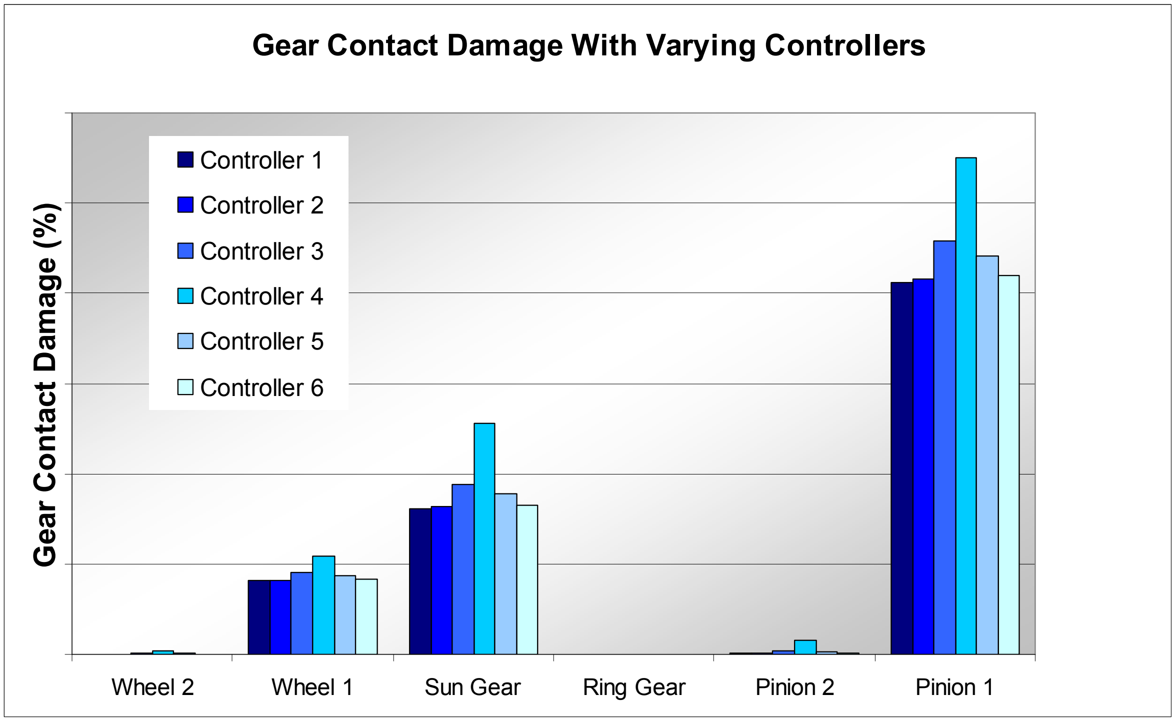


Figure 6: Gear Contact Damage with Varying Controllers

The contact damage for the gears consistently shows controller 4 as leading to the worst damage. This is as the controller generates a higher number of cycles at high torque. Controllers 1 and 2 result in the lowest damage, they have the lowest number of cycles at high torque. In this study the planet carrier position was assumed fixed (a simplification for this study) which yields different damage values for each planet gear. The model includes the rotor weight and thus main shaft bending which affects the misalignment at the planets and this misalignment depends on planet position. For a more accurate estimation of damage multiple planet carrier positions may be considered, which would lead to the same damage on each gear. In this particular example the loads on the ring gear are not sufficiently high to cause any damage; the component is in the "infinite life" region of the material fatigue curve. The bearing damage shares the same trend. The greatest damage occurs in the "LH" bearings; these are the upwind planet bearings.

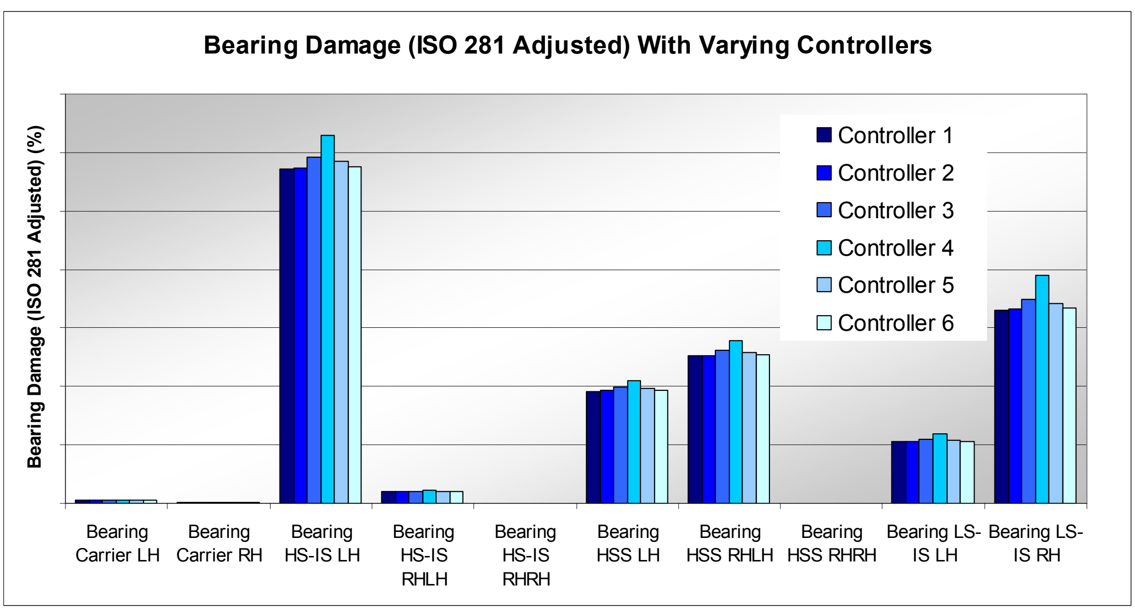


Figure 7: Bearing Damage (ISO 281 Adjusted) with Varying Controllers

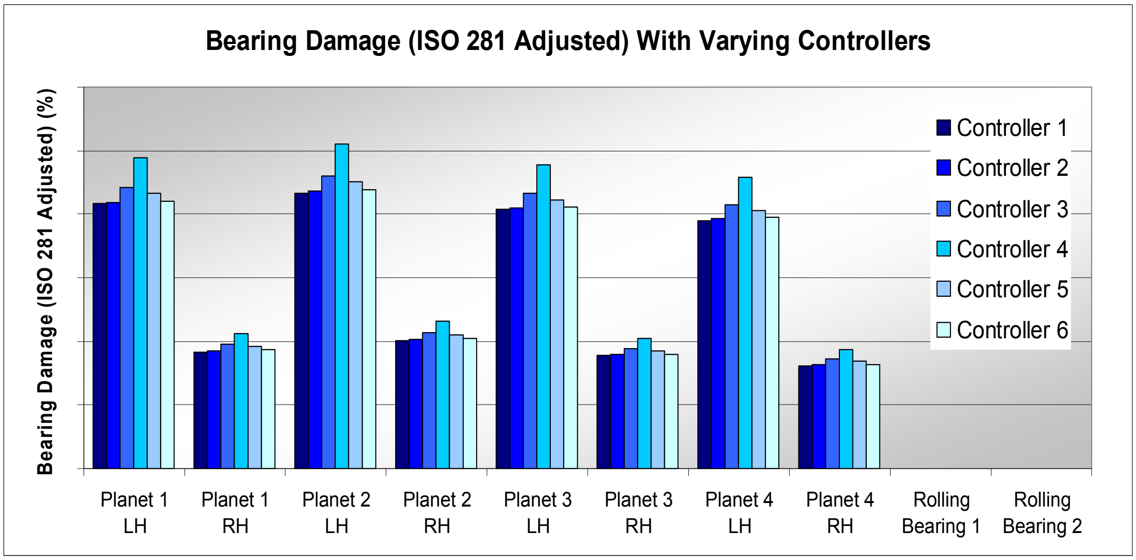


Figure 8: Bearing Damage (ISO 281 Adjusted) with Varying Controllers

Conclusions

The controller designs tested here have various properties with regard to control bandwidth, alleviation of tower fatigue and reduction of drivetrain vibrations. The comparative results obtained for the gearbox component damages illustrate the relevance of the choice of controller to failure rates over the lifetime of a wind turbine. Controllers 4, 5 and 6 used the generator torque in order to achieve some of the control objectives, thus increased the load on the drivetrain and greater wear of the gearbox components. With the help of RomaxDesigner, a comprehensive software tool for gearbox design, MLS and Romax have investigated the trade-offs inherent to different control algorithms. The approach allows different operational control strategies to be evaluated in terms of life of a critical component; the gearbox. The goal is to minimise the downtime and maximise the power production.

The analysis confirmed that wider controller bandwidth results in the increased gearbox damage. Also, the drive-train damping filter leads to the reduction of the loads. More complex control algorithms that utilise the generator reaction torque in above-rated operation result in increased loading on the gearbox. This leads to the natural trade-offs that need to be considered. The gearbox damage analysis helps with these trade-offs.

References

[1] RomaxDesigner User Manual, Romax Technology Ltd, Nottingham, UK, 2003
[2] ISO 6336-1:1996(E), Calculation of load capacity of spur and helical gears
[3] ISO 281:1990, Roller Bearings – Dynamic load ratings and rating life