Load analysis of special operation conditions and implementation of derived load states in Bearing Robustness Test (BRT)

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Abstract. Premature bearing outages at the planetary and high speed shaft stage of gearboxes are responsible for long down time periods of wind turbines \cite{1, 2}. In order to prevent premature bearing outages against certain failure mechanisms, a new robustness test procedure for original-sized WT gearbox bearings is developed within the project WT-Bearing Center NRW. The BRT serves to qualify bearings for a damage-free operation over the entire service life \cite{3}. It combines a fatigue load spectrum and also additional special load events \cite{4}. This paper describes the analysis of wind turbine loads during different operation conditions and the definition of special load events, based on this analysis. The aim of including special loads to the BRT is to consider the complex real bearing loads within the test procedure as precisely as possible.

1. Introduction

Long downtime periods burden the economic efficiency of wind turbines. Most of the downtime is caused by gearbox failures. Figure 1 shows that 59\% of all downtime of a wind turbine is caused by gearbox failures. The causes for most of these gearbox failures (67\%) are bearing outages \cite{1, 2}. Ten percent of these bearing outages occur at planetary and 70\% at high speed shaft stage \cite{5}. That implies that presently planetary and high speed shaft bearings are the main causes for long downtime periods of wind turbines.

To increase the reliability of the bearings in wind turbines, different testing methods during the product development process are used. Actual test methods investigate isolated failure mechanism like standard fatigue tests. They do not consider complex load situations of bearings or interactions in the occurrence of damage, like preliminary damages. Consequently it is not possible to replicate realistic bearing failures with the contemporary testing methods at original sized bearings of wind turbines. In order to ensure that original sized bearings of wind turbines can be tested concerning their robustness

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{Causes for down time periods of wind turbines \cite{1-3}}
\end{figure}
against certain failure mechanisms, a new robustness test procedure, the Bearing Robustness Test (BRT), is developed within the project WT-Bearing Center.NRW [4]. The aim is to develop new testing standards for original-sized planetary and high speed shaft bearings of wind turbines [3].

2. Approach of load analysis

The BRT includes a fatigue load spectrum based on field data and also additional special load events based on simulation data. The fatigue load spectrum accelerates the loads of six years to a load spectrum of about two months and covers the realistic bearing pre-damage [6] (upper path in Figure 2). The special load events comprise loads of specific operation states to include the interaction of different load conditions. The number of considered special load events inside the BRT is restricted to the number of the events actually occurring during six years of field operation (lower path in Figure 2).

The simulative analysis of specific operation states is based on simulations with a validated multi-body system (MBS) model. The MBS model is a model of the 4 MW wind turbine test facility with a state-of-the-art 2.7 MW wind turbine. It was development and validated at the CWD [7]. Within the model aerodynamic rotor input loads are calculated based on the given curves of wind speed. Electric loads affecting the generator are also included within the model. All calculation models correspond to the Hardware-in-the-Loop (HIL) system which is also used in the real testing stand [7, 8]. A sketch of the described interaction between MBS and HIL model is visualized in Figure 3. The simulation with this model enables detailed load analyses of drive train and bearing loads during system operation. Figure 4 shows exemplary simulated input loads at hub flange (drive-, tilting- and yaw torque) by a chosen mean wind speed of 17.5 m/s. The turbulence intensity was set to 12 %. It can be shown, that extreme gradients of input loads occurring during special operation states such as gusts, emergency stops, run ups and more. Duration and absolute values of gradients vary for different operation states and different wind speeds. By analysing resulting loads of different operation states concerning absolute values, load amplitudes and gradients, it is possible to characterize the operation states. The load analyses carried out for this purpose are described in the following.

So far, production states (Design Load Case (DLC) 1.2, 1.3), gusts (DLC 2.3), run ups (DLC 3.1) and emergency stops (DLC 5.1), based on IEC-load cases [9], are simulated for different values for mean wind velocity and turbulence intensity to cover all relevant transient operation states of wind turbines. Further DLCs will be considered in a second step. After simulation, resulting drive torque loads at hub flange and resulting load curves of radial bearing loads at planetary and high speed shaft stage are characterized regarding occurring maximal/minimal loads, load amplitudes and gradients as well as rotational speed values, amplitudes and gradients. The combination of load and rotational speed characterizes the complex load situation of different operation states. These characteristics of DLCs are compared to criteria of selected damage hypothesis. The comparison shows, that some of the occurring bearing loads favor certain failure mechanism more than others and in a further step, simplified loads

Figure 2. Schematic approach to create BRT

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are derived from the analysed loads of DLCs. The derived loads are then selected as special load events for the BRT. The described approach is schematically shown in Figure 5.

**Figure 3.** Interaction between multi body system model of test bench and HIL model [7]

**Figure 4.** Exemplary load simulation with multi body system model for a mean wind velocity of 17.5 m/s.

**Figure 5.** General approach for the characterization of loads and selection of special load events for Bearing Robustness Test

### 3. Load analysis of selected DLCs

The different DLCs are simulated for varying mean wind velocities. In a next step the resulting loads at hub flange as well as radial bearing loads at planetary and high speed shaft stage are analysed concerning occurring min/max values, amplitudes and gradients. Also the speed values and gradients for different stages are considered during the analysis. Figure 6 shows a summary of the load and speed ranges that occurred for the various DLCs (Run up, shut down, gust and emergency stop) at the bearing stages. The summary shows that very low loads are occurring simultaneously with low speed values.
during run ups and shut downs. The occurring gradients for speed and load are also very small for this operation state.

During gusts overloads at bearing stages are possible as the highest load values are occurring simultaneously with high speed values. The resulting gradients for speed and load are small to large for the regarded gusts.

During emergency stops medium loads and high speeds are present. Further, the largest gradients for loads and speeds occur during this DLC.

The shown load and speed ranges in Figure 6 refer to a wind turbine of the power class 2.75 MW.

![Figure 6](image_url)

**Figure 6.** Occurring load and speed ranges at planetary and high speed shaft stage during different operation conditions for the analysed wind turbine (2.75 MW)

Within the project WT-Bearing Center.NRW, the focus is set to the following bearing failures: micro pitting, smearing and fractures at bearing rips. Comparing the load characteristics of analysed DLCs with known causes for named bearing failures shows, that none of the occurring loads would directly lead to one of the named bearing failures. But some of the occurring bearing loads favor certain failure mechanism more than others do. Table 1 gives a short summary about influencing factors for micro pitting, smearing and fractures at bearing rips based on literature research. The summary indicates, that overloads during gusts combined with occurring axial oscillations can encourage micro pitting. The high load and speed gradients during emergency stops can lead to high slippage values of rolling elements and in combination with an unfavourable viscosity lead to complex load states that favour smearing. During run ups and shut downs the rotational speed is very low. Combined with axial forces, fractures at bearing rips can be encouraged. Of course, none of the analysed loads that have occurred during the different operation states are critical for bearing life time directly, but in combination with bearing pre-damages and unfavourable conditions, various operating conditions can favour certain failure mechanisms. That’s why it is important to consider the complex load situation of planetary and high speed shaft bearings within a test procedure. Therefore, simplified loads of the different operation states will be included to the BRT. This approach is described in the following.

**Table 1.** Summary about influencing factors for bearing failures [10-13]

| Failure          | Failure location | Characteristics of failure favouring state |
|------------------|------------------|------------------------------------------|
| Micro pitting    | In the running treat of inner ring | • Small slippage states of rolling element (mainly ~2 % slippage of rolling element) |
|                  |                   | • Overloads                                |
|                  |                   | • Mixed friction                           |
|                  |                   | • Critical temperature limit T ≥ 90 °C     |
|                  |                   | • Axial Oscillation                        |
**Smearing**
- At the contact surface of rolling element front surface and board, as well as in the rolling tread of inner ring and the rolling element
- Usually in the inlet of the load zone (compiles the acceleration zone)
- ~ 40 % to 80 % slippage of rolling element
- Falling below minimal load by high speed
- Huge influence of viscosity (high temperatures are critical due to low viscosity)

**Fractures at bearing rip**
- Axial forces with low rotational speed at the same time
- Tilting between inner and outer ring
- Shaft deflection

Figure 7 shows exemplary loads at planetary and high speed shaft stage during the following operation conditions: Run up, gust and emergency stop.

The mean wind velocity during shown run up is 5.5 m/s. The rotor blades start to cut in the beginning and when the rotational speed reaches a specific level, the generator is switched on. The resulting loads on the bearings of the planetary and the high speed shaft stage follow the load curve on the hub flange. The wave-like load curve at the planetary stage results from the 360 degree rotation of the planet carrier, as the tilting of the planet depends on its current position.

**Figure 7.** Load analysis of specific operation states and derivation of simplified load curves for Bearing Robustness Test
The shown gust occurs during a mean wind velocity of 12.5 m/s and the wind speed reaches a peak of 17 m/s. When the gust starts, the wind turbine starts pitch controlling to prevent possible resulting overloads. As the pitch control is slow, the input torque drops significant at the end of the gust again.

During the emergency stop the mean wind velocity is also set to 12.5 m/s. The stop is introduced by a mains failure and 3.2 s later the wind turbine starts with an emergency stop by disconnecting the generator load. Now the rotational speed is very high and the pitch control goes into a brake mode to reduce the speed again. During the emergency stop, very high load and speed gradients are occurring.

For the load analysis of different operation states, occurring min/max values, amplitudes and gradients are stored. Also simultaneously acting speed values at main shaft, planetary and high speed shaft stage are considered. Based on the stored values, simplified load curves are derived for the BRT (lower part of Figure 7). The simplified load curves for the planetary bearings are shown by the red lines and the simplified loads for the high speed shaft bearings are shown by the blue lines. In the next step, these simplified loads for run ups, gusts, emergency stops, etc. are included into the classic load spectrum of the BRT as special load events. Each special load event is considered in number equal to its real occurrence frequency, determined on the basis of real measurement data form comparable systems. The evaluation of wind turbines of the same performance class in Denmark has shown that approx. 2000 start-up processes take place in one year. Further approx. 200 emergency stops occur per year and correspondingly it comes to approx. 1800 normal shutdown processes per year. The frequency of gusts depends strongly on the definition of the time duration and the definition of the height of the wind speed rise and in a first step an estimated value for a specific gust shape is taken into account.

Figure 8 shows the configuration of the BRT. The special load events are combined with the fatigue load spectrum, so that the accelerated loads are interrupted at an almost corresponding load level by the dynamic load events. The load events for run ups, gusts, normal shut downs and emergency stops take in total approx. 10 seconds each. By considering 2000 run ups per year, 1980 normal shut downs per year, 1000 gusts per year and 200 emergency stops per year, the total test time is expanded by approx. 80 hours.

By including the special load events in the BRT according to their real frequency of occurrence and load characteristics, the BRT includes all load conditions to which a bearing of the planetary and high speed shaft stage is exposed in the first 6 years in field operation.

4. Conclusion

Premature bearing outages at the planetary and high speed shaft stage of gearboxes are responsible for long down time periods of wind turbines. In order to prevent premature bearing outages against certain failure mechanisms, a new robustness test procedure for original-sized WT gearbox bearings is developed within the project WT-Bearing Center.NRW. In contrast to actual test methods of original sized wind turbine bearings, the BRT includes the complex load states of real operation conditions to reproduce realistic bearing damages at original sized wind turbine bearings.

To consider the complex load states of real operation conditions within the BRT, special load events are defined based on a detailed load analysis of different operation states. The chosen operation states are extracted from the defined DLCs in IEC 61400-1. A comparison of analysed loads with known causes of certain bearing failures shows, that some DLCs can favor specific bearing failures more than others. Based on the characteristics of these loads, special load events for the BRT are derived to ensure...
that the test loads correlate with the realistic loads as good as possible. The derived special load events are scattered into the BRT according to their real frequency of occurrence, so that the BRT contains all relevant loads of the first 6 years and finally serves a new standard for bearing testing.

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