Characterization of the High-Speed-Stage Bearing Skidding of Wind Turbine Gearboxes Induced by Dynamic Electricity Grid Events

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CHARACTERIZATION OF THE HIGH-SPEED-STAGE BEARING SKIDDING OF WIND TURBINE GEARBOXES INDUCED BY DYNAMIC ELECTRICITY GRID EVENTS

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Bearing behavior is an important factor for wind turbine drivetrain reliability. Extreme loads and dynamic excitations pose challenges to the bearing design and therefore its performance. Excessive skidding of the bearing rollers should be avoided because it can cause scuffing failures. Excitations coming from wind and the electricity grid can subject the drivetrain to fluctuating torque and nontorque loads. Wind-induced excitations have been investigated predominantly in literature. However, modern wind turbines are subjected more and more to grid-induced loads because of stricter electricity grid regulations. For example, during fault-ride-through events, turbines are required to stay connected for a longer period of time during the grid failure. This work investigates the influence of electrically induced excitations on the skidding behaviour of the tapered roller bearings on the high-speed stage of a wind turbine gearbox. This skidding behaviour during dynamic events is described as a potential bearing failure initiator by many researchers; however, only limited full-scale dynamic testing is documented. Therefore, a dedicated grid-loss-type event is defined in the paper and conducted in a dynamometer test on a full-scale wind turbine nacelle. During the event, a complete electricity grid failure is simulated while the turbine is at rated speed and predefined torque levels. Particular focus is on the characterization of the high-speed shaft tapered roller bearing slip behavior. Strain-gauge bridges in grooves along the circumference of the outer ring are used to characterize the bearing load zone in detail. It is shown that during the torque reversals of the transient event, roller slip can be induced. This indicates the potential of the applied load case to go beyond the preload of the tapered roller bearing. Furthermore, the relation between the applied torque and skidding level is studied.

1. Introduction

A wind turbine converts wind energy into electricity. The rotor harvests energy from the wind and is connected to a drivetrain, consisting in general of a main shaft, a gearbox, and a generator. A turbine is designed for a commercial life of 20 years. The loading on the drivetrain is of multiphysical nature, since it originates from variations in the wind and electric excitations. Accurate insights in these loading conditions are needed for high-quality turbine design. Assessment of wind loading is determined by local conditions at the specific wind site. Simulation models can be used to predict wind flows at the site [1]. These models are often validated by means of short-term measurement campaigns using wind masts or lidar approaches. The wind loads result in multidegree of freedom loads combining torque and nontorque loading. Extensive literature is available investigating these loading types. Electrically induced excitations in the drivetrain, on the other hand, are documented less in literature.

Nonetheless, for modern machines these excitations are becoming increasingly important, because of stricter grid regulations. Turbines are required to remain connected to the electricity grid for longer periods during full or partial electricity grid loss. During such an event, the drivetrain is fully unloaded and then completely reloaded. In case the grid-loss persists beyond the defined time limit the turbine disconnects from the grid and can perform an emergency stopping event. Pao et al. indicate that such an emergency stop can cause damage to the machine [2]. The excitation resulting from a grid-loss event influences all subcomponents of the power train. This paper focuses on the high-speed stage (HSS) of the gearbox, particularly the response of the HSS to the loss of counter-torque and the HSS tapered roller bearings (TRBs). Several authors indicate the possible link between significantly changing operating conditions and HSS bearing failure. Heidenreich et al. show the importance of torque reversals on the oil film thickness in bearings in wind turbine gearboxes. The reduced film thickness could explain premature failure [3]. In addition to torque reversals, misalignments between gearbox and generator influence bearing life. Whittle et al. show generator bearings are susceptible to skidding caused by misalignment, whereas gearbox bearings should be less influenced by radial misalignment [4]. Struggl et al. similarly conclude that rapid load variations, combined with misaligned gear shafts in the HSS, can lead to undesirable axial load cycles at the bearings [5]. Stadler et al. discuss premature bearing failure related to white etching crack phenomena and discuss the tentative industrial common ground on the cause of this issue as being related to the large variety of operating conditions, stresses that might exceed strength (e.g., loading, dynamic conditions), as well as environmental and/or other factors (e.g., lubrication, contaminants such as water, and stray current)[6]. Strong variations in operating conditions combined with misalignments are therefore suspected to cause bearing degradation. This paper investigates the capability of a grid loss-type event to induce these conditions in the HSS TRBs.

2. Approach

This paper intends to show the influence of an electric grid-loss event on bearing skidding in the HSS of the wind turbine gearbox by means of an experimental approach. A dedicated load case based on a grid-loss-type event is defined. The main goal of the event is to induce the torque reversals that many authors indicate as the possible cause of premature HSS bearing failure. The event will experimentally characterize TRB roller behaviour and show that roller skidding is induced during the torque reversals of the dynamic event.

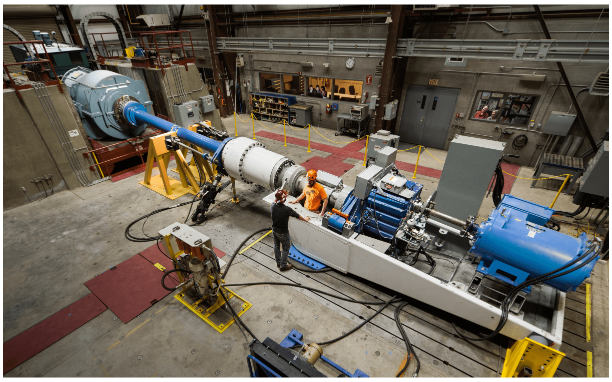

Figure 1: Experimental setup on test rig. Photo by Mark McDade, NREL 32734.

To perform the experiment under controlled conditions, dynamometer testing is used. The boundary conditions for the gearbox and generator determine the misalignment between them. Therefore, a wind turbine nacelle dynamometer is well-suited for the experiments. Figure 1 shows the setup on the NREL 2.5-MW dynamometer. The test article is the turbine nacelle of the Gearbox Reliability Collaborative 750-kW wind turbine. The advantage of this system, and more particularly of its gearbox, is its design is in the public domain and it has a significant instrumentation package consisting of external and internal instrumentation. The latter is highly pertinent to this work, as there is detailed instrumentation at the HSS TRBs. Figure 2 shows the strain gauges that are placed on the circumference of the outer ring of the TRBs at 0°, 90°, 180°, and 270°.

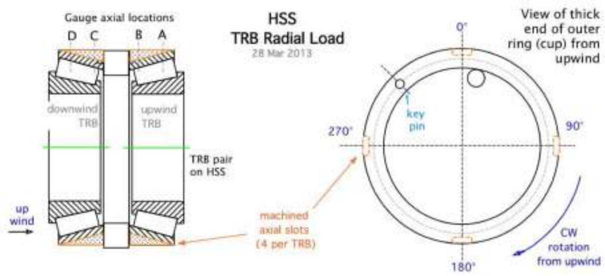

Figure 2: Strain-gauge instrumentation at HSS TRBs.

The applied load case is a severe type of grid loss. The system starts in normal operating conditions. The rpm is at its nominal value, whereas the power produced can vary from 25% of the nominal value to the nominal value. At the initiation of the grid loss, the generator is decoupled from the electricity grid, while the rpm is still at nominal conditions. This results in significant torque reversals that gradually damp out. The rpm is brought to zero in a controlled manner over two minutes. No additional breaking is applied in order to have only the influence of the torque reversals on the system behaviour. Figure 3 shows the corresponding load cases for 25% and nominal power. Torque reversals are clearly visible. These reversals are induced at a frequency corresponding to the eigenfrequency linked to the main drivetrain modeshape of the complete dynamometer system [7].

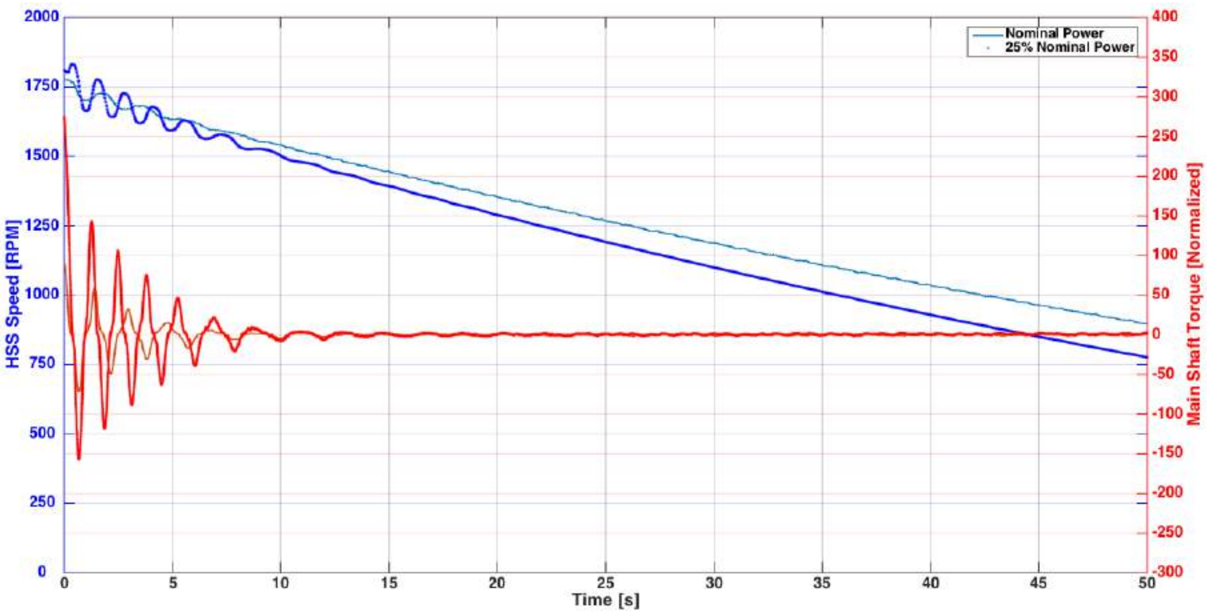

Figure 3: Grid-loss load cases for different initial conditions.

3. Bearing skidding characterization

The strain gauges along the circumference of the HSS TRB can be used to detect skidding of the rollers. Rotating systems have characteristic frequencies. For bearings, the main frequencies are the ball-pass frequency related to the inner ring, the ball-pass frequency related to the outer ring (BPFO), fundamental train frequency, and the roller spin frequency related to the roller speed [8].

The strain gauges at the outer rings of the TRBs can be used to monitor the BPFO. The gauges are at fixed locations along the outer ring circumference and, as such, the BPFO gives insights in the roller speed behaviour when the rollers pass those specific fixed strain-gauge locations. The BPFO determines how many elements are passing by that specific gauge in a specified amount of time. Monitoring the BPFO frequency during the event shows the differences in timing of the passages of the different rollers. We look at one specific strain-gauge location along the circumference of the outer ring. If all rollers were to have the same perfect kinematic motion, then the BPFO would be visible at one discrete frequency line. The time between each passing roller would be exactly the same for each passing; however, if a given roller experiences slip, then the kinematic motion will not be perfect and the timing between the two consequent roller passages will change. Therefore, the BPFO will be visible at multiple frequency lines in the spectrum, which we will refer to as "smearing" of the BPFO.

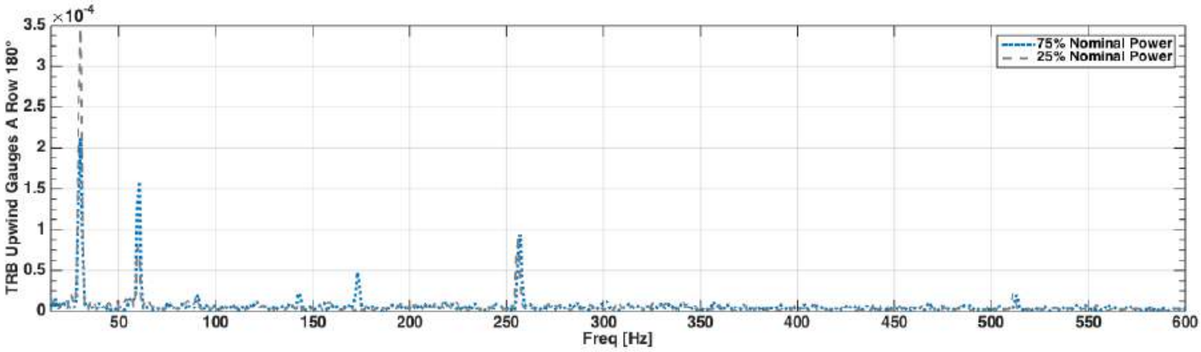

Figure 4: Comparison of strain-gauge spectrum for TRB position A on 180° circumference during constant load and rpm conditions for different initial loading conditions.

Figure 4 shows the frequency spectrum for the strain gauge at the 180° position during constant torque and rpm conditions prior to the dynamic event for the two load cases. The 180° position was chosen because it has proven to be the most susceptible to skidding during torque reversals [9]. A Hanning window was used to minimize the leakage effect. The HSS excitation frequency at 30 Hz is clearly visible for all three initial loading conditions. The BPFO at 255 Hz and its multiple at 510 Hz are also significantly pronounced. All peaks are distinct and span only one frequency line. The BPFO amplitude stays approximately the same for all three loading conditions. This could be explained by the fact that the rpm in all three cases is the same and the bearing loads do not exceed the applied preload. The amount of slip in the rollers is therefore highly limited.

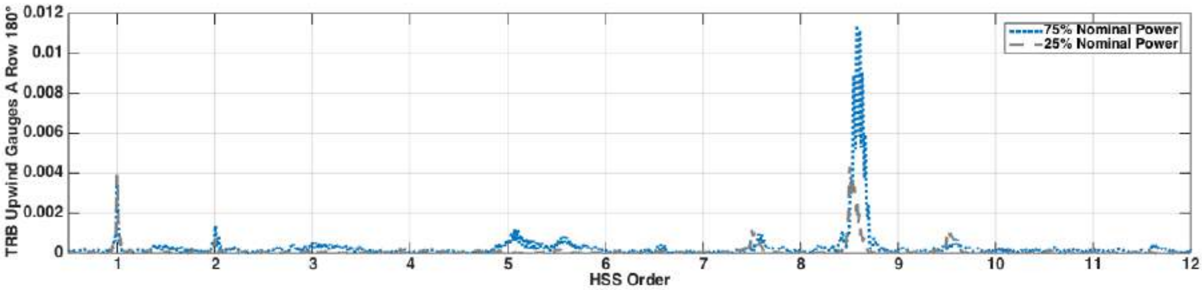

Figure 5: Comparison of strain-gauge spectrum for TRB position A on 180° circumference during torque reversal for different initial loading conditions.

During the torque reversals, bearing system behaviour changes significantly. To use the BPFO to assess roller timings, it is necessary to compensate for the speed fluctuations present in the system.

Speed changes will also cause shift in the BPFO and could therefore be incorrectly interpreted as bearing slip. To filter out these effects from the spectrum, angular resampling is used. This approach transforms the measured strain signal from the time domain to the angular domain using the HSS encoder. In essence, instead of sampling at a constant time rate, the strain signals are sampled based on a constant angular rotation rate of the HSS. By sampling angularly, the influence of speed variations is filtered out because samples will always be taken at identical angular increments regardless of the actual speed of the shaft. Figure 5 shows the angular resampled spectrum of the $180°$ position strain-gauge signal. The HSS frequency is at a distinct peak at 30 Hz. The BPFO, on the other hand, shows significant frequency "smearing." Moreover, the amplitude is still significantly dependent on the initial power level. Therefore, it can be concluded that during the torque reversals, roller slip occurs even for preloaded TRB bearings. The complex loading mechanisms active during the grid-loss event change the load zone in the TRB to the extent that the TRB preload is insufficient and the rollers start to show excessive slip. Moreover, it can be concluded that the power level at which the grid-loss event is triggered is directly linked to the amount of slip the TRB rollers are experiencing.

4. Conclusions

This paper showed the potential of a dynamic grid-loss event to cause mechanical system degradation in high-speed stage bearings by triggering excessive slip. It was shown that grid-loss-type events induce torque reversals driven by the first drivetrain resonance. The load changes during these reversals can induce slip in the TRBs and correspondingly initiate failure in the system.

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