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A possible relation between wind conditions, advanced control and early gearbox failures in offshore wind turbines

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Abstract

During the past decades, great efforts have been undertaken to make wind power a competitive source for electrical energy. By the end of 2012, global installed wind capacity had risen to 264GW, almost a tenfold increase of the capacity in 2002. Nevertheless, the wind energy sector is still far too expensive to be profitable, especially the strong growing offshore branch. However, a significant part (about 25%) of the cost is related to operation and maintenance (O&M), in particular the failures of the main components (i.e. gearbox and drivetrain) resulting in long downtimes and hence high O&M costs. Various studies today discuss if condition monitoring systems, which allow the forecasting of failures at a very early stage, might be the cure to the problems related to the reliability of the gearbox. Rather than formulating yet another methodology to forecast upcoming failures, the aim of this paper is to identify the underlying cause of the reliability issues related to the gearbox.

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Keywords: wind turbines; gearbox failure; reliabilty; control

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1. Introduction

The growth of the wind energy industry over the past three decades has been staggering. Until a few years ago deployment growth rates in Europe were around 25-30% annually and even nowadays similar growth rates are seen worldwide. Despite the recession in the EU over the last few years growth rates of around 10% are maintained in this part of the world. In the beginning of 2013 a total of 264GW was installed worldwide, and with an average capacity of 1MW, this means that more than 250,000 machines are currently in operation. Since the majority of these wind turbines are designed using a standard lay out using a low speed main shaft connected to the hub with the rotor blades, a gearbox and a generator, (Figure 1), it is evident that wind turbines are a large market for gear box manufacturers. Contrarily to ordinary industrial gearboxes wind turbine gearboxes are designed for a reversed mode of operation, since power needs to be transferred from the low speed shaft to the high speed shaft. Furthermore the ingoing rotational speeds are extremely low, typically in the range of 10-20 RPM where outgoing rotationally speeds usually comply with the range common to Megawatt scale electrical motor/generators, hence in the order of 750-1500 RPM.

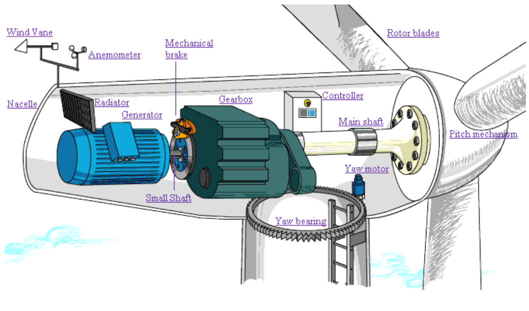

Fig. 1. Typical layout of drive train components in a modern wind turbine, with a hub carrying three blades, a main low speed shaft, a step-up gearbox and a high speed connection shaft to the generator

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This requires gearboxes to be designed with 3 to 4 stages, usually in a hybrid fashion: a combination of one or two planetary and one or two parallel stages Transferred power is in the range of 2-7.5MW, which make the design of such gearboxes a highly specialized and high tech activity. Despite the large amount of efforts to carefully design such gearboxes up to a typical lifetime of 20 years, their implementation into the complete wind turbine provided to be a challenging, and troublesome.

Over the last decade, when the sizes of the state-of-the-art wind turbines went into the 2MW+ range with diameters of around 100m, it became evident that gearboxes designed for these machines did not comply with the demanded design life time of 20 years. Quite a few new wind turbine designs of several manufacturers showed gearbox problems that turned out to be cumbersome. Gearbox manufactures were blamed for not delivering according to specifications and were forced to provide modified gearbox designs. This has even led to complete fleet gearbox replacements for machines recently placed into the market. Especially when the wind turbines were located offshore, where maintenance activities are complicated and expensive, this caused long downtimes and a considerable increase in operational expenditure.

Figure 2 provides the breakdown of the downtime of a 36 unit offshore wind farm in front of the coast of The Netherlands. In the respective year 10 gearboxes had to be replaced, and this was the major cause of the low availability.

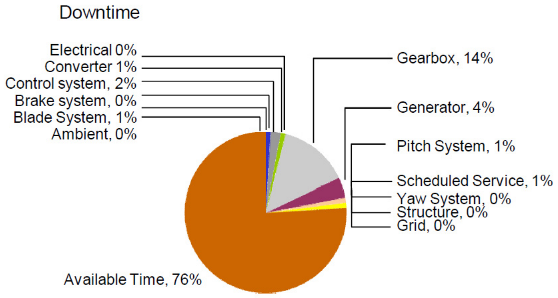

Fig. 2. Experienced downtime and experienced availability of the OWEZ offshore wind farm Egmond aan Zee NL in 2008

2. Wind turbine power control

Wind turbines operate in various environmental conditions. At typically 3-4m/s the machine starts producing power as shown in Figure 3. Below such wind speeds the wind turbine is not rotating, because a parking brake prevents this, or alternatively, the wind turbine controller allows the rotor blade to rotate in an idling (at very low RPM) mode without any power takeoff. Around this 3-4m/s wind speed grid connection is established and the rotor starts operating at a rotational speed that assures maximum power output at each wind speed. This means that with increasing wind speed, the RPM of the wind turbine increases proportionally, maintaining its optimal power extraction mode. At around 12 m/s the electrical capacity of the generator is reached, and from that wind speed onward the control mode is changed into constant speed, blade pitch control. Pitching the blade (or feathering the blade) is necessary in order to not overload the gearbox and the generator. In the ideal control mode (generator) power is kept constant independent of the wind speed (above 12m/s). At a typical wind speed of 25m/s the control system brings the rotor to a stop by completely feathering (unloading) the rotor blades and finally applying the (mechanical) parking brake.

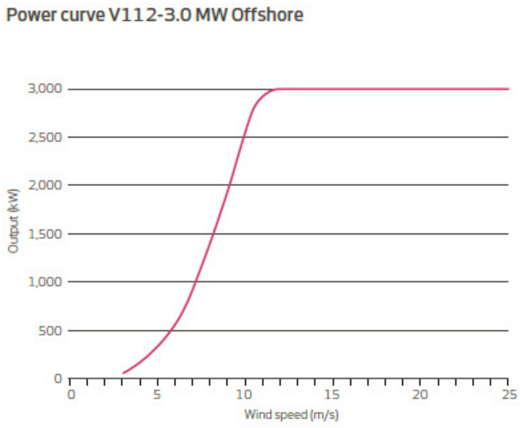

Fig.3. Power (P-V) curve of a modern wind turbine showing a cut-in (starting) wind speed of around 3-4m/s and a rated wind speed of around 12m/s.

3. Loads on wind turbine gearboxes

As can already be understood from the power curve of a typical wind turbine, the loads on the drive train are a function of the incoming wind speed. But also at a given (average) wind speed, the instantaneous wind speed may fluctuate significantly due to ambient turbulence. In the range of wind speeds between cut-in and let's say 10 m/s this may lead to large power fluctuations which can only be partially mitigated by excursions around the RPM "belonging" to the corresponding average wind speed. Needless to say that this has a large impact as well on the gearbox loads.

A similar issue holds above the rated wind speed, where it is aimed to keep the power constant by continuous blade pitching activity at a constant RPM. In the ideal case this mode of operation does not contribute to load fluctuations in the gearbox. Usually the largest contributions to drive train load fluctuations are found around the rated wind speed (~ 12m/s) and during start and stop actions of the machine in the operational range of wind speeds (4-2m/s).

4. Advanced blade pitch control and its impact on drive train loads

One of the more recent options that has been investigated and implanted is the use of individual (IPC) or collective (CPC) pitch control of the rotor blades. In this IPC or CPC control option the blades are cyclically pitched over one revolution. IPC means that each blade follows an individual blade pitching control signal over a revolutions, where CPC means that for each azimuth angle the blade pitch is prescribed. The main reason for implementing such an option is the anticipated reduction of cyclic loads on the rotor blades which are caused by wind shear and by yawed operation. Wind shear is a physical property of the atmospheric boundary layer, which leads to a wind speed increase with increasing height, as shown in Figure 4. With the rotor diameters of the present wind turbines (which may go beyond 150m) this wind shear indeed leads to cyclic aerodynamic loads. The same holds for yaw misalignment. This is a situation in which the wind turbine nacelle is not properly aligned with the wind direction, and this also gives yield to cyclic load fluctuations on the blades. In principle the control system tracks wind direction changes, so in a (10 minute) time averaged sense there is no yaw misalignment. But within a 10 minute average direction large scale turbulences also create wind direction changes of typically + 10-15 degrees, and the yaw system (yaw bearing and yaw motors, shown in Figure 1) is too slow to anticipate these wind directional changes.

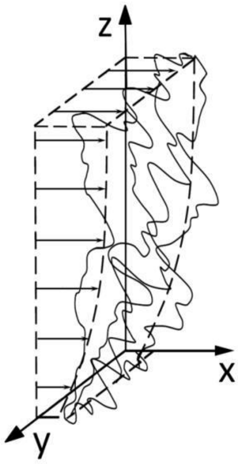

Fig. 4. Visualization of wind shear and turbulence. Directional changes are present as well in a turbulent wind field but are difficult to visualize in a graph like this.

With wind turbine blades in blade length equal (or even larger) than the span of the largest commercial aircraft it might be wise to try to mitigate such blade load fluctuations. IPC or CPC pitching actions are a possibility to reduce such blade load fluctuations. This has been identified by a number of wind turbine manufacturers and few of them, a.o. Vestas, GE-Wind, Siemens and MHI (Mitsubishi) have implemented IPC or CPC in their products.

A major factor complicating the implementation of IPC or CPC is the need of “a priori” information about the wind or about the loads on the blades. This has hampered the effective introduction of IPC/CPC significantly. Manufacturers started implementation of either IPC or CPC in the middle of the last decade, based upon simulated loads calculated by typical commercial software load simulation packages such as Bladed, Flex5, HAWC2, Fast or equivalent. These software packages are typically time domain simulations which are coupled with wind field simulators to provide the load calculation with a good representation of the operational environment.

So in principle the loads on the rotor can be determined for all possible combinations of average wind speed, turbulence intensity, yaw misalignment, rotational speed and blade pitch control. Usually such integrated load calculations are performed by the wind turbine designers in the wind turbine company and the resulting load spectrum is forwarded to the sub-suppliers of the components, such as the blade manufacturer, and the sub-suppliers for the drive train components, the yaw system and the towers.

Apart from the blade manufacturers the drive trains sup-suppliers were not able to perform similar calculations, simply because the wind turbine manufacturers wanted to keep part of the design information proprietary. That specifically holds for the details of the design of the control systems (both the power control and the blade pitch load control).

Hence the gearbox manufacturers were not completely informed about the total system for which they had to design their gearboxes. Of course they were provided with a complete load. But how well did these load spectra represent real operational conditions? That evidently is entirely dependent upon the quality of the simulations, as well as on the quality control of the design, the manufacturing and the assembly process. Errors and inaccuracies in all these phases may affect all components in terms of their experienced loads and hence their life-time cq maintenance demand.

With respect to the inaccuracies in the simulations there are of course many issues. Here the effect of inflow conditions is assessed. Figure 5 shows the measured relation between 10 minute average wind speed and turbulence intensity. As explained above the wind speeds of major interest for load fluctuations can be found around the rated wind speed (~ 12m/s).An average turbulence intensity of 15% is found for this wind speeds, but it is also evident that there is a large variation present. The bandwidth is roughly between 12% and 20%, where also occasionally very low turbulence levels are found.

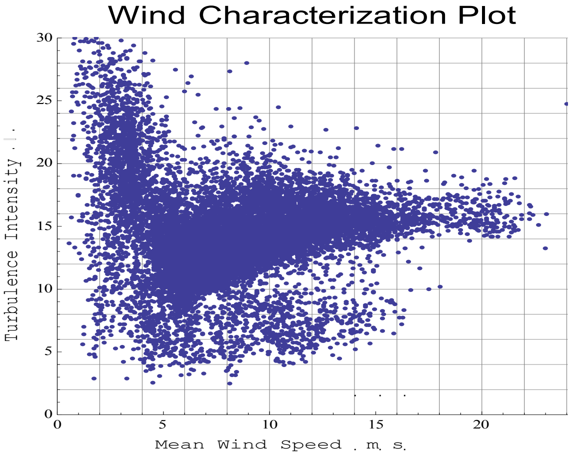

Fig. 5. Turbulence intensity as a function of average wind speed experienced at the OWEZ offshore wind farm.

Simulations are usually run at one turbulence level per wind speed class only, and for offshore that is usually around 12%, so lower than experienced. But the major issue is the large differences in turbulence intensities. These may lead to large fluctuations in the torque and hence in the dynamic loads on the gearbox. Unfortunately there is no public information available about actual gearbox loads, but using existing literature [4] we may get an impression about such loads, as shown in Figure 6, which shows the edgewise blade root moments at 13m/s for a turbulence intensity of 15%.

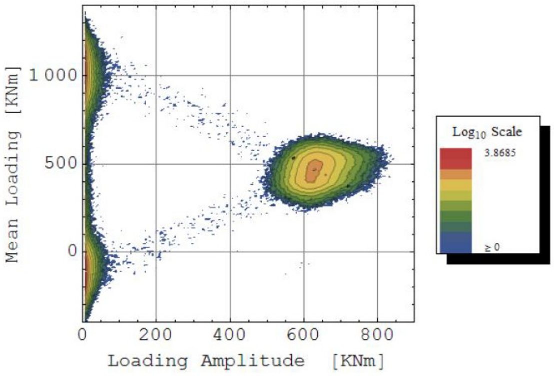

Fig. 6. Counting matrix for the turbine operation at 13 m/s and turbulence intensity of 15% [4]

What can be seen from this graph is that the gravity loads on the blade are dominant. When the wind turbine is rotating the weight of the blade provides a cyclic load of around 600kNM. But it can also be observed that there are significant periods where the wind turbine is not producing, and the rotor is either in standstill or is idling. Then the blade load is steady or very slowly varying and provides a mean load between roughly -200kNM and +1200kNM, depending upon the azimuthal position of the blade. These values comply again with the 600kNm gravity load. Also a few transients can be seen from idling to operation and vice versa.

5. Conclusions

Down to the present day, the issues with the gearbox reliability are a well-known concern of project developers as well as insurance companies. Much effort has been spent in increasing their reliability. The turbine, as well as the gearbox design itself, is continuously improved to finally match the design life time of 20 years. Nevertheless, it is difficult to design a reliable gearbox without the knowledge about the real operational conditions.

Already minor increases in this knowledge might lead to an improved gearbox design, such as more advanced blade control or the incorporation of the real turbulence.

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