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TOWARDS THE ZERO MAINTENANCE WIND TURBINE

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ABSTRACT

Renewable sources are set to form an increasingly important component of electricity generation in the UK and worldwide. Wind turbines are the most developed renewable technology and are now the largest renewable source for electricity in the UK. Most new turbines are currently being sited onshore but offshore sites could harness greater resource with higher wind speeds and lower turbulence. However, the offshore environment means that access to the turbines is more difficult and attendance for maintenance will be extremely limited, especially during the winter months. This means to ensure high turbine availability, and therefore a high cash return for operators, high reliability turbines with condition-based maintenance will be essential for offshore wind turbines. The paper will present ongoing work at Durham on three inter-related projects, first studying the reliability of existing onshore turbine, then analysing the failure modes and effects on turbines and finally designing a condition monitoring scheme for offshore turbines based on this knowledge.

INTRODUCTION

The installation of off-shore wind turbines for the exploitation of the huge wind energy resources in marine environments represents the most important opportunity for further development of this technology. The reliability of the entire system will play a central role in the design, construction and installation of competitive wind turbines [1]. Despite substantial improvements in recent years, the current reliability of the onshore wind turbines is still inadequate for the harsher environment offshore [2]. This is due to two causes: firstly, reduced accessibility of the site, especially in the winter periods, dramatically decreases the energy harvest in the case of a severe failure; secondly, the cost of specialized personnel and equipment is substantially higher (e.g. the crane vessel, required for heavy maintenance operations). Offshore operation and maintenance (O&M) costs can be quantified as five to ten times higher than on land [3].

This paper presents a combined approach of reliability studies, failure modes and effects analysis (FMEA) and condition monitoring as a solution to these problems. The reliability studies take real turbine population data and use statistical analysis to derive information about the behaviour of groups of turbines. The results from two studies are presented here: firstly, for turbines grouped over the entire population and recording interval; secondly, turbines grouped by manufacturer and model. The FMEA is a subjective analysis that gives a qualitative description of turbine. Condition monitoring is conducted on individual plant and provides information about the state of a particular turbine. To keep costs down and make a system attractive to operators, condition monitoring must be focused on those faults and failure modes that are most important, as identified by FMEA and reliability studies. Condition monitoring is a technique for raising the availability of an installed turbine whose failure modes are understood.

RELIABILITY STUDIES

A quantitative analysis of real wind turbine failure data has shown important features of failure rate values and trends [4, 5]. Figure 1 shows the results from WindStats [6] and LWK [7] data for large German and Danish populations of wind turbines compared with the failure rate of other electricity generation technologies.

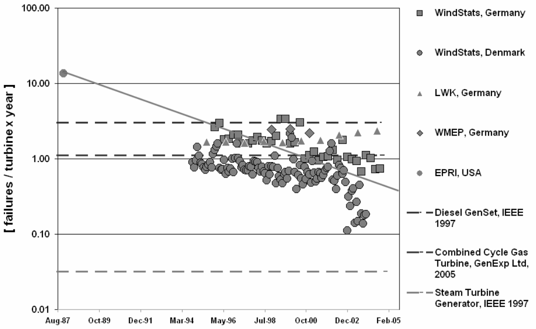

Figure 1. Wind turbine failure rate in comparison with other generation technology.

One of the most important results concerns the general downward trend in the failure rate of the two national populations. The application of a Power Law Process (PLP) to the data has demonstrated that for the German turbines, despite their complexity, there is still a substantial margin of improvement of the failure rate due to a relatively younger and hence less mature technology. This constitutes an important opportunity for the development of future wind turbine designs and is contrary to some observers who have been advising that offshore developments should include turbines of lower complexity than have already been installed. However, these studies did not take into account of differences between different architectures of wind turbines.

Comparing Turbine Design Concepts

The main disadvantage of WindStats data is that the failures are reported in a grouped form for the entire population of wind turbines over the recording period. The population includes a heterogeneous sample of turbines of different ages and technologies and only the average behaviour can be extracted. Conversely the LWK data segregates the information into each turbine model so a direct comparison can be made between different turbine architecture. In particular, it is possible to compare the failure patterns of indirect drive, fixed or variable speed machines which require a gearbox, and direct drive, variable speed machines, in which the power output from a synchronous generator is delivered to the grid through a fully rated converter. The gearbox has typically been considered a main cause for concern in the wind energy industry due to its O&M costs.

The five turbine types considered in the LWK survey have been organized in two groups of different rating. Group 1 contains smaller machines of about 500 kW and group 2 are rated above 800 kW. The average failure rate has been obtained through the application of a Homogeneous Poisson Process model, under the assumption that the failures occur randomly over the observed period. The basic assumption is that there is neither reliability improvement nor deterioration of the systems reliability over the entire observed period. For the turbine models considered, the analysis has been reiterated over each subassembly. This represents the lowest level of indenture of the structure of the machine, and no further information is given about failure modes. The number of turbines involved in the survey is in the order of tens, a population that can be considered sufficient for a significant analysis given the length of the recording interval, that is, one year.

The calculated failure rates for the two groups are shown in figure 2. It is striking that the failure rate of all electrical related subassemblies play a fundamental role in the overall reliability of the machines, particularly for the direct drive Enercon machines. The synchronous generator, in particular, shows a failure rate that is about twice that of the induction generator for indirect drive turbines. The Mean Time to Repair (MTTR) of the generator is substantial, especially for large synchronous machines, and each failure in this component consistently decreases the availability and, more generally, the economic performance of the turbine. The possible causes of the unreliability of the synchronous generator have been investigated and discussed by Tavner et al. [8]. Two main factors are likely to be the cause: firstly, the larger diameters imply a more difficult sealing from the environment, exposing the generator to insulation damage due to the presence of humidity or other contaminants in the air; secondly, there is insufficient standardization in the manufacturing of the machines as a consequence of smaller production runs for such slow speed machines. From the previous observations, an improvement of the generator performance appears to be crucial to improve the performance of the direct drive concept.

The contribution of electric subassemblies to the overall failure rate of the turbine is substantial and independent of the design concept. This subassembly group aggregates failures from many disparate components, such as switchgear, transformer, cables and controls. However, whilst electric subassemblies may have a relatively high failure rate their MTTR is generally low so their effect on availability can be judged to be low but no further consideration is made of these issues here.

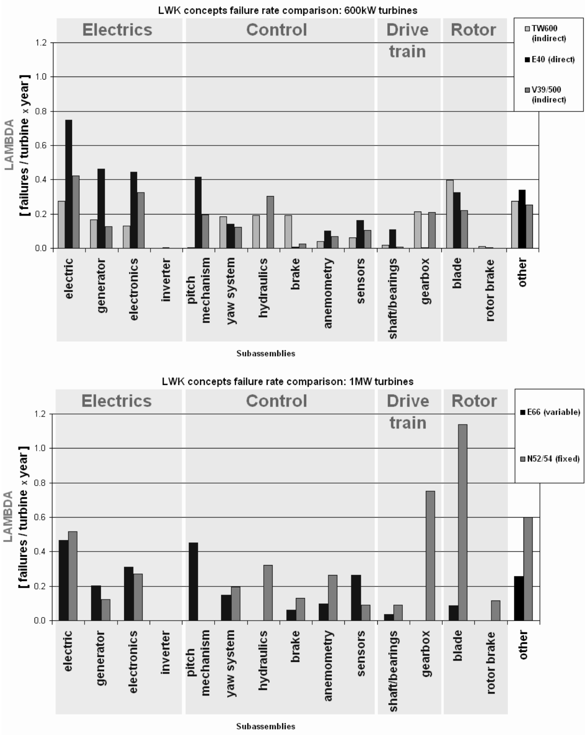

Figure 2. Turbine failure rates. Top: group 1 (small); bottom: group 2 (large).

Failures in mechanical subassemblies, particularly the gearbox, dominate the reliability of the fixed speed machines, which also produces a high MTTR. The combined failure rate of the inverter and electronics for the direct drive shows a similar figure to that of the gearbox box for fixed speed turbines. This fact is crucial since these two concepts are in direct competition for the development of a high reliability turbine. However, the application of a PLP to WindStats has shown the reliability growth curve for the gearbox to be flat, independent of the population of wind turbines. In other words the gearbox can be considered a mature technology, so no substantial improvement can be predicted for this subassembly. This observation is particularly important in the comparison between direct and indirect drive turbines. A final observation is that data appear to confirm the better reliability performance of the hydraulic pitch control to the electric one.

FMEA

FMEA is a subjective analysis tool, which uses a qualitative approach to identify potential failure modes, their initiating causes and the associated risk to a system when in the design, manufacture or operational phase. FMEA is carried out in industry by a team consisting of design and maintenance personnel whose experience encompasses all the factors considered in the analysis. These are:

- Item name and function
- Possible failure modes
- Probability of failure mode occurrence
- Initiating causes of failure mode
- Effects of failure mode: immediate, intermediate and end effects
- Failure mode severity
- Current failure detection methods in place
- Compensating provisions to reduce the risk of a failure mode

As a result of the FMEA, a numerical value is assigned to the individual failure modes in order to highlight particular areas of risk. This is done by considering three of the above factors associated with the failure mode:

Severity: To what extent the failure affects the capital operation of the system.
Occurrence: How likely the failure mode is to initiate.
Detection: How likely failure is to be detected using current condition monitoring and inspection techniques.

The above factors are individually rated using a numerical scale, typically ranging from 1 to 10. These scales, however, can vary in range depending on the FMEA standard being applied. The risk priority number, RPN, is then calculated as follows:

$$\text{RPN} = \text{Detection} \times \text{Occurrence} \times \text{Severity}$$

The RPNs of the individual subassemblies of a system are then summed to obtain its total RPN. It must be noted that these values are purely dependant upon the analyst's engineering judgement and knowledge of the system being analysed, hence the subjectivity of FMEA.

FMEA Findings

The FMEA performed on a typical 2 MW indirect drive, variable speed turbine in this study has shown that there is a correlation between the RPN and measured failure rates of wind turbines from the first part of the paper. Furthermore, this trend has also been demonstrated by comparison with further industrial failure rate data, as shown in figure 3.

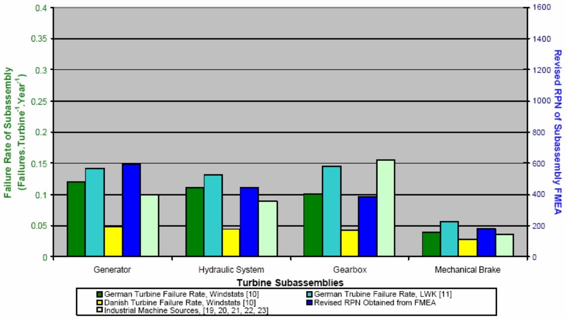

Figure 3. Comparison between measured failure rates from the WindStats and LWK surveys, industrial failure rate data and FMEA RPN predictions for key subassemblies in a wind turbine.

The FMEA also enables the prediction of the number of failure mode occurrences and the initiating causes. This is important for design and maintenance staff to understand. The different natures of the initiating causes have been tallied and are illustrated in figure 4.

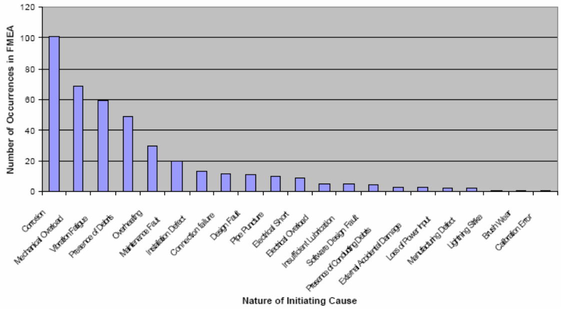

Figure 4. Occurrences of Different Initiating Causes of Failure Modes in FMEA.

The analysis shows that material failure is the most frequently occurring failure mode. It is mostly the result of corrosion, vibration fatigue, or mechanical overloads and indicates the weakening of the material. This nature of failure mode is mainly brought about by the following initiating causes: corrosion; vibration fatigue; and mechanical overload. As shown in figure 4, these initiating causes are the most common

Material failure mainly affects the blades and frame of the gearbox and generator, all of which are critical to the wind turbine. This highlights the fact that special attention needs to be paid to all these subassemblies that exhibit high initial RPNs. Material failure, however, mostly has low impacts upon the affected subassembly as normal operation can usually continue until it is repaired. Irrespective of this, material failure is usually very difficult to detect and, if allowed to progress, it can have more serious implications. Another frequently occurring failure mode is fracture, resulting from mechanical overload or shock forces. The nature of a fracture implies that material cohesion is lost, leading to failure of the affected subassembly. The subassemblies seriously affected by fractures are the blades and gearbox gear teeth, which are critical components in the wind turbine. Fracture therefore carries a higher risk than material failure as it also endangers personal safety.

Of all the failure modes identified, it was found that there were 212 separate occurrences spread across twelve of the wind turbine subassemblies in the studied turbine. These failures were brought about by 410 initiating causes, noting that it is possible for a failure to be due to more than one possible initiating cause.

CONDITION MONITORING TEST RIG

A test rig has been established to act as a model for a wind turbine and to allow the investigation of failure modes identified in the previous work to develop an appropriate condition monitoring system. This test rig has the benefit of allowing additional instrumentation, without the need for site access. This work takes as a starting point Jefferies & Infield [9] who able to detect the presence of unbalance and defects in the blades of a small wind turbine by measuring the power spectrum density at the terminals of the turbine's generator. The rig, shown in figure 5 comprises a DC motor, rated at about 50 kW; a two stage gearbox; and the prototype SLiM generator. The generator is a low speed, low mass, high inertia machine based on the design of Spooner et al. [10]. The spoked structure is designed to allow the machine to have a large radius to achieve high flux cutting speeds and therefore acceptable voltages from a direct drive generator, capable of achieving multiple MW outputs within an acceptable mass. Although the generator is of unusual topology, it is harmonic rich and has a number of clearly identifiable modes, which have been determined through modal analysis.

Instrumentation

A significant part of the test rig is the instrumentation system, which enables a variety of wind speed data to be applied, relevant data collected from the drive train and the terminals of the generator, then correlated with the input conditions. It is important to note that many wind turbines operate at variable speed. The test rig can simulate the torque input due to transient and gusting wind conditions by applying either real or simulated wind speed data using the computer-controlled DC drive system. This input then stimulates torsional harmonics in the drive train, which in turn will be modulated by defects in the system.

A number of transducers have been fitted to the rig to measure shaft speed, shaft torque, and shaft vibration. A torque transducer was positioned between the gearbox and the generator to measure the shaft torque directly, however, with different generator topologies the torque will be measured from voltages and currents. Eddy current proximity sensors were positioned to measure the vibration of the shaft between the gearbox and generator. Two sensors, positioned at 90° to each other, were used to enable vibration to be measured in horizontal and vertical axes. Proximiters were appropriate, rather than accelerometers, because of the low frequency of the vibrations. The lag between speed demand and actual speed became more important at higher frequencies and the transfer function of the power converter was unknown, so a tachometer was used to determine the shaft speed and the signal also fed to the instrumentation system. An accelerometer has been included to monitor the gearbox for vibrations relating to tooth faults and bearing failures.

Test Rig Results

A normal FFT is inappropriate because of the long duration of the measurements and the non-stationary nature of the wind driving torque. A spectrogram is used, which is a short time FFT. This yields a three dimensional representation of the frequency response of the rig with time. Measurements of the torque signal resulting from the rig being excited by real wind data under different conditions are given in figure 6 and this shows the detectable difference measured in the test rig torque when faults are applied to the generator.

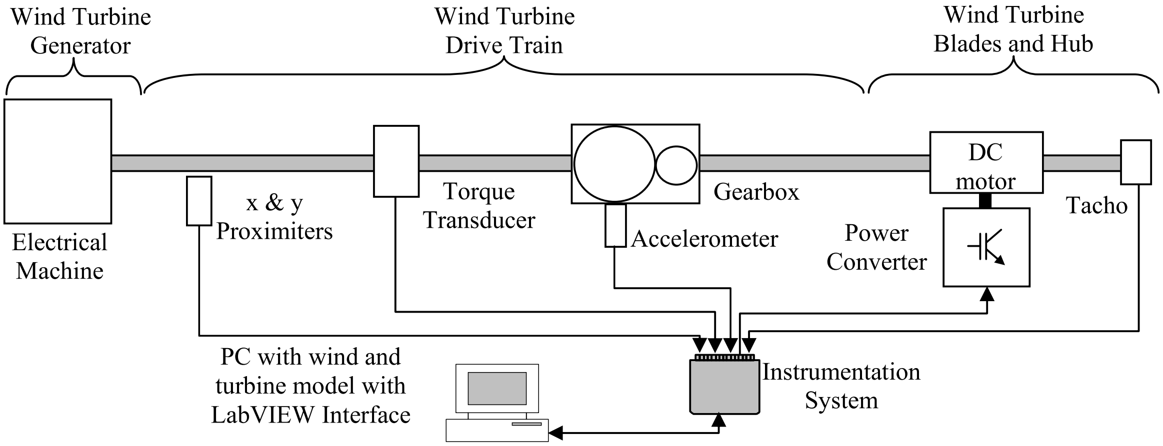

Figure 5. Control and instrumentation interface with the test rig.

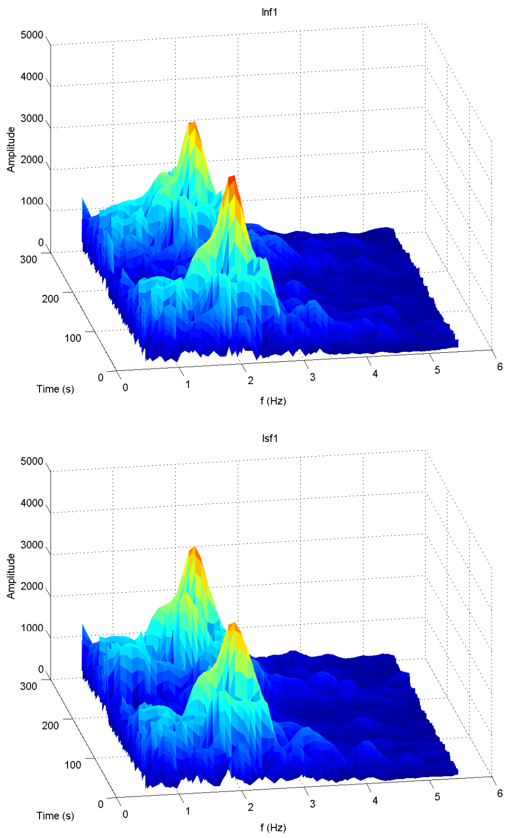

Figure 6. Spectrograms of test rig torsional response to real wind data excitation for frequencies below 5 Hz with: (upper) normal conditions; (lower) single coil fault.

CONCLUSIONS

Reliability studies of Danish and German data have shown that wind turbines generally have an improving failure rate. Comparison between turbines of different concept have shown that indirect drive turbines appear more reliable, despite the fact that they incorporate gearboxes. Electrical subassembly failures dominate the reliability of direct drive concept wind turbines. In particular, the slow speed synchronous generator shows a failure rate double that of the higher speed induction machine. This may be due to the larger diameter, leading to sealing and insulation problems, because insulation over longer, slow speed, windings makes them statistically more prone to a failure. The gearbox is confirmed to be a major problem of the indirect drive configuration. Direct comparison between the aggregate failure rate of inverter and electronics shows them to have higher failure rates than gearboxes, nevertheless the higher MTTR of a gearbox makes this subassembly problematic.

FMEA enables the prediction of wind turbine failure rates, giving manufacturers a better idea as to how reliable new or existing wind turbine designs will be. It has also highlighted potential risks with current indirect drive wind turbine concepts. The failure modes to be addressed by turbine condition monitoring have been identified together with the subassemblies which should be more closely observed. These results have been incorporated into the Condition Monitoring Test Rig.

The Condition Monitoring Test Rig has demonstrated that wind speed driving excites an array of harmonics in the drive train enabling the natural frequency of the main components and faults in the generator to be detected. Work on the signal processing of individual signals from the Test Rig has shown a positive improvement in signal to noise ratio detected, suggesting that these techniques can be applied to a full-size turbine.

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