

SUPERGEN **Wind Energy Technologies Consortium**



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EXECUTIVE SUMMARY

The main purpose of this monograph is to provide an overview of the research that has been carried out in the Phase 1 of SUPERGEN Wind project, from March 2006 to March 2010. A number of achievements have been made across different topics of the project in the Phase 1, with a large number of papers published in international journals and conferences, with both national and international collaborators.

The project is briefly introduced in Section 1, with its objectives listed in Section 2. The main achievements in Phase 1 are summarised in Section 3, which highlights the accomplishments of the project in terms of technical output.

Section 4 lists the research carried out in four Themes, each has multiple research topics. The abstracts of published papers or the executive summary of deliverable reports are included in the monograph for each research Theme and research topic.

In Theme W Baseline Wind Turbine Performance, the outputs were grouped into five research topics: Reliability and availability analysis, Turbine instrumentation, measurement and data processing, Turbine configuration, Wake development and interactions, and Forest canopies effect.

In Theme X Drive-train Loads and Monitoring, the outputs were grouped into two research topics: Turbine blade, electrical and mechanical characteristics and Condition monitoring systems.

In Theme Y Structural Loads and Materials, the outputs were grouped into four research topics: Wake effects on blade loading, Novel materials, Structural blade model, and Tower & blade load reduction.

In Theme Z Environment Issues, the outputs were grouped into three research topics: 1. Foundation scour, 2. Turbine Radar Cross Section (RCS), lightning protection and wind farm radar model, and 3. Interaction of structural, lightning protection and RCS issues.

The research in Phase 2 of the project is also introduced briefly in Section 5.

The Consortium Partners as well as their collaboration areas are listed in Appendix A. All publications are listed in Appendix B, and the project contact details can be found in Appendix C.

ACKNOWLEDGEMENT

The SUPERGEN Wind project was established by the Engineering and Physical Sciences Research Council (EPSRC Grant Ref EP/D034566/1) in 2006 as part of the Sustainable Power Generation and Supply (SUPERGEN) Programme, later became part of the Research Councils UK Energy Programme.

The Consortium would like to express their sincere appreciation to EPSRC and the Research Councils UK for their support.

They also acknowledge the support and help provided by their industrial partners, which include Amec, Areva, Senergy, E.ON UK, Garrad Hassan, HR Wallingford, NaREC, QinetiQ, Romax, Scottish Power, Smart fibres, and Vestas. Special thanks to Dr Dave Pearce in E.ON, Dr David Quarton in Garrad Hassan, and Dr Ashley Crowther in Romax for their active support for the project.

Table of Contents

- Executive Summary iv
- Acknowledgement..... v
- Table of Contents..... vi
- 1 Introduction 1
- 2 Phase 1 research objectives..... 1
- 3 Phase 1 main achievements..... 2
- 4 Phase 1 research and outputs 6
 - 4.1 General outputs 6
 - 4.2 Theme W: Baselining wind turbine performance..... 8
 - 4.2.1 Introduction 8
 - 4.2.2 Research deliverables..... 8
 - Reliability and availability analysis..... 9
 - Turbine instrumentation, measurement and data processing 15
 - Turbine configuration 17
 - Wake development & interactions 18
 - Effect of forest canopies 23
 - Other publications..... 25
 - 4.3 Theme X: Drive-train loads and monitoring..... 26
 - 4.3.1 Introduction 26
 - 4.3.2 Research outputs 26
 - Turbine blade, electrical and mechanical characterisation..... 27
 - Condition monitoring system 37
 - 4.4 Theme Y: Structural loads and materials 39
 - 4.4.1 Introduction 39
 - 4.4.2 Research outputs 39
 - Wake effects on blade loading..... 40
 - Novel materials..... 41
 - Structural blade model 43
 - Active load reduction 45
 - Other publications..... 50
 - 4.5 Theme Z: Environmental issues..... 51
 - 4.5.1 Introduction 51
 - 4.5.2 Research outputs 51
 - Foundation scour 52

Radar Cross Section, lightning protection, and wind farm radar model 53

Interaction of structural, lightning protection & RCS issues 56

5 Phase 2 research..... 57

Appendices..... 58

Appendix A Consortium..... 58

 A.1 Academic partners 58

 A.2 Industrial partners 59

 A.3 Academic and industrial collaboration 60

Appendix B Publications by author alphabetic order 61

 B.1 Books 61

 B.2 Journal papers 61

 B.3 Conference papers..... 62

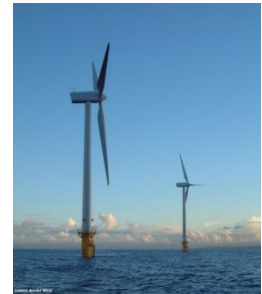
Appendix C Project staff and students 67

Appendix D Project contact details 69

1 INTRODUCTION

The Engineering & Physical Science Research Council (EPSRC) has funded its SUPERGEN Sustainable Power Generation and Supply Programme to the tune of more than £40M forming Consortia of international standing to research the future of electrical power generation.

The latest announcement of the fifth tranche of work, SUPERGEN V, includes the Wind Energy Technologies Consortium (EPSRC Grant Ref EP/D034566/1), which started from 23rd March 2006 and ends on 22nd March 2010, with value £2.55M.



Wind energy is rapidly evolving in response to climate change as wind technology has demonstrated its effectiveness as a low carbon supplier, with Europe installing over 10,163 MW of wind energy, 39% of the total energy installed in 2009. The UK's long exposed coastline and low mountain ranges give it Europe's largest wind resource. Larger wind turbine (WT) sizes, needed for acceptable Cost of Energy (COE), still require research to ensure cost-effective access that resource.



The multidisciplinary Wind Energy Technologies Consortium is lead by University of Strathclyde and Durham University and consists of 9 Research Groups with expertise in Wind Turbine Technology, Aerodynamics, Hydrodynamics, Materials, Electrical Machinery & Control, Reliability & Condition Monitoring.

The Consortium has the active support of 13 Industrial Partners, including Wind Farm Operators, Manufacturers & Consultants.

Phase 1 of the project completed in March 2010. During this phase, the Consortium has made a number of achievements in various research topics, with a high number of papers published in international journals or conferences. To provide an overview of the research that has been carried out in the project, this monograph is produced, with introduction to each research topic, followed by research outputs in each of them. Abstracts of each deliverable are listed in this document.

2 PHASE 1 RESEARCH OBJECTIVES

The challenge facing the Consortium is significant encompassing the search for engineering solutions to:

- improve the efficiency and reliability of wind energy.
- reduce the cost of energy production.
- facilitate the siting of machines in off-shore locations.
- reduce the impact on existing infrastructure.

During Phase 1 of the project, the Consortium's overall aim was

"To undertake research to improve the cost-effective reliability & availability of existing and future large-scale wind turbine systems in the UK".

To achieve such aim, the objectives of the research in SUPERGEN Wind were identified to be:

- To quantify from available data the reliability and availability of wind turbines as a function of a number of criteria.
- To define commonly used turbine/farm configurations and to explore possibly radical alternatives for the offshore environment.

- To develop new/improved predictive models for turbine wake development in off- and on-shore wind conditions, and for the effects of topography, in order to assess aerodynamic loads on large turbines.
- To produce models of the mechanical, electrical and material failure modes of wind turbines for use in a condition monitoring package.
- To develop an integrated condition monitoring system for a wind turbine or wind farm capable of allowing predictive and proactive maintenance.
- To explore the potential of innovative materials in wind turbine blades and towers to achieve load and mass reduction.
- To develop methods for on-line determination of aerodynamic characteristics to improve regulation of wind turbines.
- To ascertain the amount possible and means of active load reduction in large wind turbines and to determine size related limitations.
- To assess potential design limits (e.g. rotor diameter, tower height, etc.) in future wind turbine development.
- To develop modelling representations of scour-hole development and to find tower shapes that minimise scour.
- To provide means of minimising visibility to radar systems and maximising turbine lightning protection for farms of large wind turbines.

3 PHASE 1 MAIN ACHIEVEMENTS

With the aforementioned objectives, the Consortium has made a number of achievements across different aspects of wind turbine. They are summarised below with images of some of the work are given in this section.

- *Identified causes of turbine unreliability and low availability*

Reliability analysis of WTs has been established by the Consortium and through interaction with European partners, using public data, we have identified the key turbine subassemblies causing downtime. These data show that 75% of all failures are responsible for only 5% of the annual downtime and the remaining 25% of failures cause 95% of the downtime.

Failure Rate and Downtime from 2 Large Surveys of European Onshore Wind Turbines

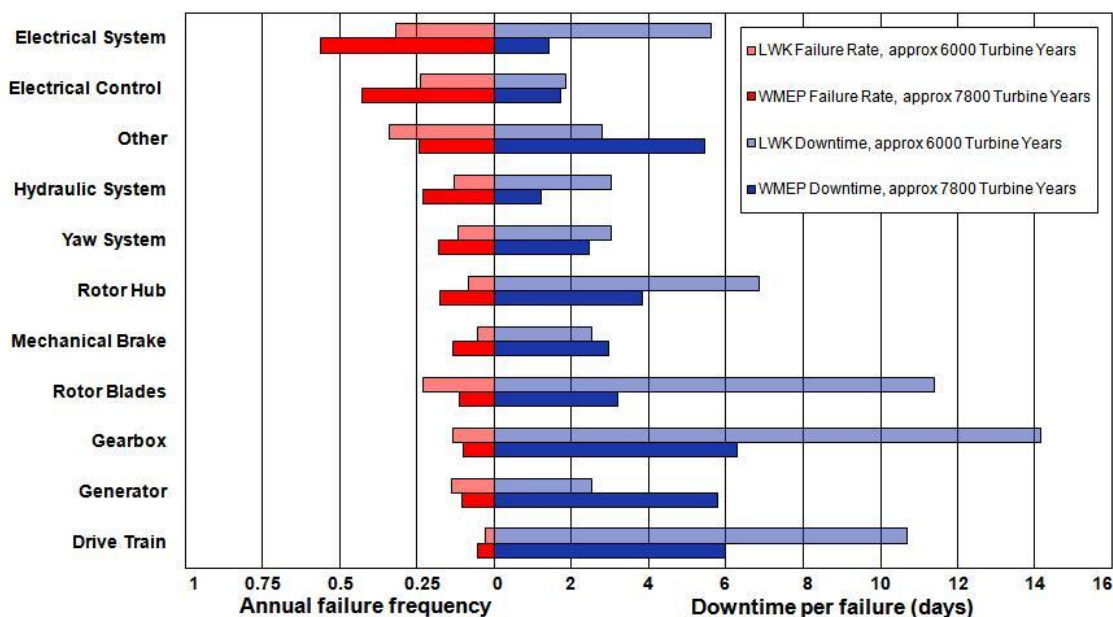


Fig. 1. Using a presentation developed by ISET, showing the reliability and downtime from two surveys including more than 15000 turbine years. Extracted by the Consortium in collaboration with ISET & TU Delft.

- *Identified how and where condition monitoring can improve turbine availability.*
The Consortium has reviewed commercially available WT condition monitoring packages and identified their strengths and weaknesses. This is being disseminated to the industry. In the light of the reliability and availability work above new condition monitoring techniques are being developed for WTs to improve effectiveness of early fault detection on the 25% of faults that cause the majority of downtime.
- *Developed and demonstrated algorithms for tracking of fault frequencies in variable speed turbines.*

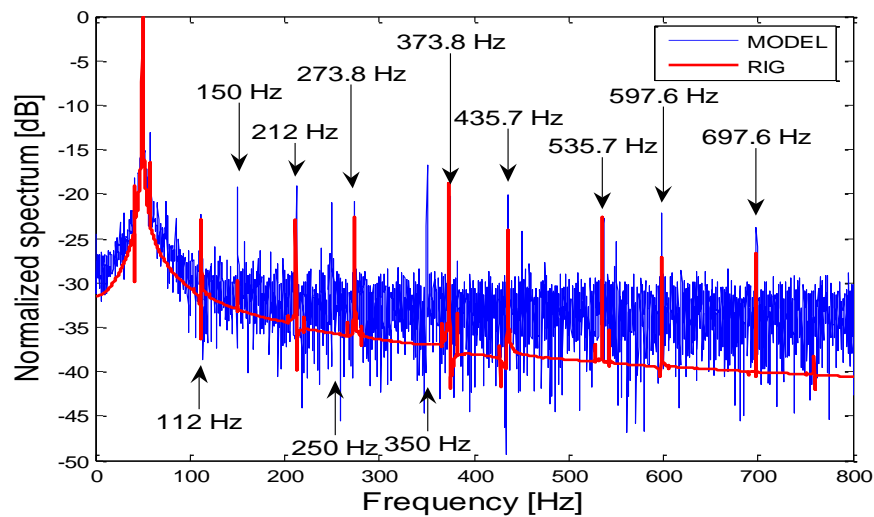


Fig. 2. DFIG stator current spectrum for operation with stator OC fault

- *Identified control improvements to reduce WT tower and rotor loads with reductions up to 50%.*
In large multi-MW WTs the production loads are a major contribution to lifetime equivalent fatigue loads on towers and blades. Loads on both can be reduced by improving WT controllers. Advanced solutions to the control design have reduced tower loads by 15-18% without compromising the WT performance. Similarly blade loads can be reduced by individual blade control, which has attracted interest from Industrial Partners.

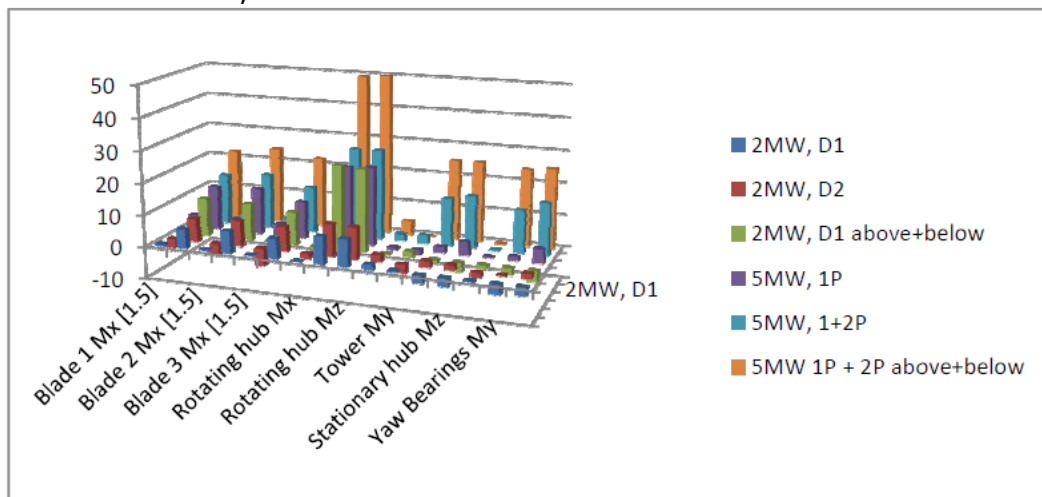


Fig. 3. Load reduction for wind turbine.

- *Producing high quality single and array models and measurements for turbine wakes.*
Wind tunnel simulations have been set up with multiple, rotating, speed-controlled 5MW size model WTs in same-scale off- and on-shore neutral atmospheric boundary layers (ABL) and measurements made of all three velocity components, turbulence intensities, Reynolds

stresses and other quantities. Measurements have also been made of wakes in a correctly scaled, stably stratified, off-shore ABL. Data gained is of direct interest to industry for improving currently inadequate methods and understanding. A wake/ABL rotor aerodynamic unsteady loading model has been developed.



Fig. 4. Typical wake effects, which the Consortium are modelling, observed on a large offshore wind farm.



Fig. 5. Wind farm wake measurements being undertaken by the Consortium.

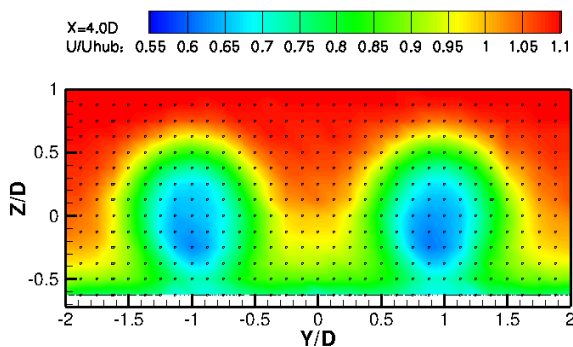


Fig. 6. Consortium wind tunnel measurements of velocity 4D downwind of two scale-model WTs 2D apart.

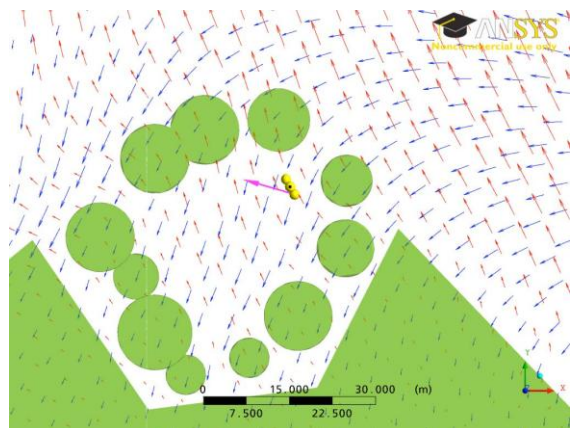


Fig. 7. Consortium CFD flow simulation around a forest clearing. High level wind vectors, above canopy, in blue and low level wind vectors in red.

- Produced robust single and array Radar Cross Section (RCS) turbine models. Computationally efficient models developed for studying interaction between improved lightning performance and reduced RCS, focused on the impact of WTs on marine navigational radar. Work has been well received by Industrial Partners. Derived and published fundamental new analysis on WT blade lightning strikes, which has fed into the latest revision of the standard IEC 61400-24.



Fig. 8. Wind farm radar cross section (RCS) models developed by the Consortium.

- Investigated and testing new composite materials to improve blade strength and durability.* New composite interlayer reinforcements (hybrid veils) developed that increase blade structure fatigue life by half an order of magnitude, while simultaneously increasing toughness threefold in bonded connections. This has improved damage tolerance without accompanying disruption in blade manufacturing processes. New structural fibres also evaluated that confirm order of magnitude improvements in blade spar cap fatigue life.

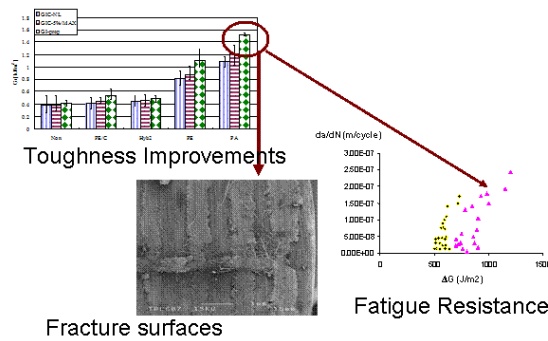


Fig. 9. New blade interlayer materials increases toughness with improved fatigue performance.

- Developed new materials to reconcile the simultaneous reduction of RCS and improvement of lightning performance.* Novel layers have been introduced into the composite that incorporate metal coated fibres in a non-woven layer. This has reduced RCS and increased electrical conductivity in the laminate without causing any associated reduction in blade strength.
- Developed fully parametric blade model for the assessment of innovative materials, condition monitoring effectiveness, and "smart" blade performance.* A parametric blade model, comprising a script-driven pre-processor to the Abaqus finite element program, has been developed. The script enables parametric studies of the positioning of key structures, the application of true aerodynamic loading, as blade surface pressure, and the assessment of the importance of improvements in material properties. An extension to the model has been made to aid interpretation of results from the NAREC biaxial resonant load fixture.

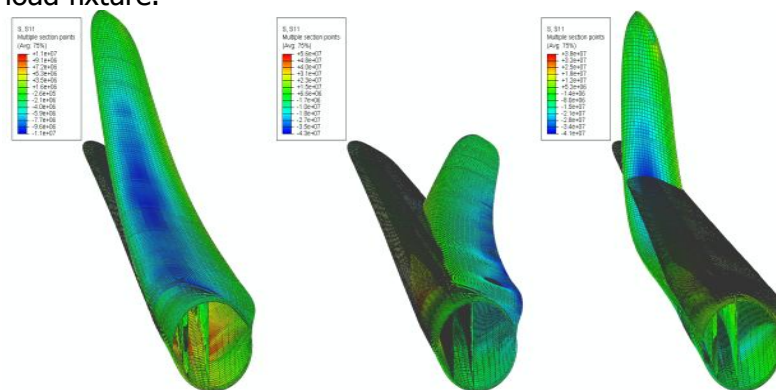


Fig. 10. WT parametric blade model developed by the Consortium.

- Modelled & tested the prediction of scour around offshore turbine foundations.* A detailed understanding of the relationships between the hydrodynamics, bed profile, and pile geometry is required for scour mitigation. Detailed flow measurements were taken from a series of tank experiments and the data is being analysed. A new, efficient numerical model of current induce scour was developed. Special attention was given to choice of turbulence model which was validated against published data.



Pressure sensors

Fig. 11. Photo of Consortium test tank showing a circular monopile and pressure sensors.

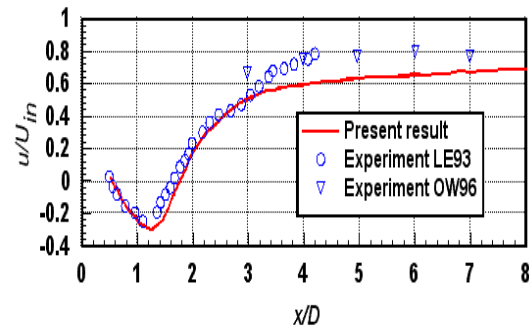


Fig. 12. Mean centreline component of stream velocity around turbine foundation in Fig. 9 from Consortium hydrodynamic model showing comparison with experimental data.

4 PHASE 1 RESEARCH AND OUTPUTS

4.1 General outputs

The following book section/papers have been published by the Consortium as general outputs in Wind Energy area.

Leithead WE, (2007) Chapter 5 Wind Energy, Energy... beyond oil, Eds: Fraser Armstrong and Katerine Blundell, doi: ISBN-10: 0199209960, Oxford, PP 71-83.

http://books.google.com/books?id=RnrNX0GbVdWC&source=gbs_navlinks_s

INTRODUCTION

A wind turbine or even a wind farm, i.e. a group of wind turbines, is becoming an increasingly familiar sight in the countryside today. The wind turbine converts the power in the wind to electrical power and consists of a tower, rotor, typically with three blades as in Fig. 5.1, and a nacelle containing the power converter.

From its rebirth in the early 1980s, Wind Power has experienced a dramatic development. Today, other than Hydropower, it is the most important of the renewable sources of power. With an installed capacity equivalent to that required to provide electricity for over 19,000,000 average European homes and annual turnover greater than £5,500,000,000, Wind Energy has exceeded its year-on-year targets over the last decade. This growth in the contribution to electricity generation from Wind Power in Europe is likely to continue over the next few years since the EU Commission has set a European target for 2010 of 12% of electricity generation from renewable sources. In the long term, the achievable limit to the contribution of Wind Power is estimated to be 30% of the total European demand, an amount almost equal to the installed nuclear capacity.

In the UK, Wind Power is the fastest growing energy sector. Over 4,000 people are employed by companies working in the wind sector and it is estimated by the DTI that the next round of offshore wind development could generate a further 20,000 jobs. In a 2003 Energy White Paper, the UK Government aspired to achieving a 60% reduction in UK CO₂ emissions by 2050. In order to do so, it has set targets for UK electricity generation from renewable sources of 10% of electricity demand by 2010 and 20% by 2015. Since it is the most mature of the renewable energies, much of these near term targets must be met by Wind Power. Irrespective of whether these targets are achieved, the potential for increase in the UK is substantial.

The prospects for Wind Power development in the UK are dependent on the available wind resource, public acceptance and technical development. Each of these issues is discussed below.

Leithead WE, (2007) *Wind energy*, Philosophical Transactions of the Royal Society A, Vol. 365, No. 1853, pp. 957-970. Access online: <http://dx.doi.org/10.1098/rsta.2006.1955>

ABSTRACT

From its rebirth in the early 1980s, the rate of development of wind energy has been dramatic. Today, other than hydropower, it is the most important of the renewable sources of power. The UK Government and the EU Commission have adopted targets for renewable energy generation of 10 and 12% of consumption, respectively. Much of this, by necessity, must be met by wind energy. The US Department of Energy has set a goal of 6% of electricity supply from wind energy by 2020. For this potential to be fully realized, several aspects, related to public acceptance, and technical issues, related to the expected increase in penetration on the electricity network and the current drive towards larger wind turbines, need to be resolved. Nevertheless, these challenges will be met and wind energy will, very likely, become increasingly important over the next two decades. An overview of the technology is presented.

Tavner PJ, (2008) *Wind power as a clean-energy contributor*, Energy Policy, Volume 36, Issue 12, pp. 4397-4400. Access online: <http://dx.doi.org/10.1016/j.enpol.2008.09.033>

ABSTRACT

Modern wind turbines are complex aerodynamic, mechanical and electrical machines incorporating sophisticated control systems. Wind turbines have been erected in increasing numbers in Europe, the USA and elsewhere. In Europe, Germany and Denmark have played a particularly prominent part in developing the technology, and both countries have installed large numbers of turbines. This article is concerned with understanding the historic reliability of modern wind turbines. The prime objective of the work is to extract information from existing data so that the reliability of large wind turbines can be predicted, particularly when installed offshore in the future. The article uses data collected from the Windstats survey to analyse the reliability of wind turbine components from historic German and Danish data. Windstats data have characteristics common to practical reliability surveys; for example, the number of failures is collected for each interval but the number of turbines varies in each interval. In this article, the authors use reliability analysis methods which are not only applicable to wind turbines but relate to any repairable system. Particular care is taken to compare results from the two populations to consider the validity of the data. The main purpose of the article is to discuss the practical methods of predicting large-wind-turbine reliability using grouped survey data from Windstats and to show how turbine design, turbine configuration, time, weather and possibly maintenance can affect the extracted results.

4.2 Theme W: Baseline wind turbine performance

Theme leader: Loughborough University

Partners: Durham University
Loughborough University
Rutherford Appleton Laboratory
Surrey University
University of Strathclyde

4.2.1 Introduction

Research assessing the expected reliability and availability of wind turbines has been seen as an important priority within Europe. It has been suggested that operations and maintenance costs for offshore wind farms could contribute up to 30% of the energy costs. With onshore operations and maintenance costs at around 10-15%, it can be seen that there is a need for strategies to reduce wind turbine failure rates.

Before developing a strategy for increasing the reliability and availability of wind turbines, a certain amount of baseline information is required. The purpose of this theme was to provide this baseline information which would feed into the subsequent themes. In particular, to research and define existing wind turbine reliability & availability; to define the exemplar wind turbine configuration for future large scale off-shore machines; to define appropriate wind characteristics for wind farms in complex environments, e.g. near forests and offshore.

4.2.2 Research deliverables

The research outputs are grouped by five research topics in this theme.

- Reliability and availability analysis
- Turbine instrumentation, measurement and data processing
- Turbine configuration
- Wake development & interactions
- Effect of forest canopies

Reliability and availability analysis

A detailed statistical analysis of available data on failures will not only provide a prediction model for existing wind turbine failures but will also pinpoint those components that are most prone to failure and have the greatest impact on wind turbine operation and indicate how wind turbines should be designed to optimise reliability and availability.

The papers included in this topic describe the work conducted by the Consortium to provide a benchmark of reliability information about onshore wind turbines taken from publicly available data. In general it has not been possible to obtain data from wind turbine manufacturers or operators because of issues of commercial confidentiality. However, from presentations made by the Consortium to the industry it is quite clear that the data contained herein represents a reasonable benchmark for the future.

Reliability information on offshore wind turbines is only now starting to appear and the Consortium hope that they will be able to report data from that experience in 2009/10.

If wind turbine operators are able to plan timely maintenance of their machines, then information regarding likely availability will be very important. At present, availability models are based on mean turbine availability with no real breakdown by component, age or failure mode. Maintenance offshore could be more effectively targeted with more detail in terms of what is likely to fail when, paying attention to the age and type of the wind turbine. One report has been produced for availability analysis. In this topic, onshore and offshore meteorological data will be used to determine likely access times for repair of different components in order to estimate the weather-related dependence of Turbine Availability.

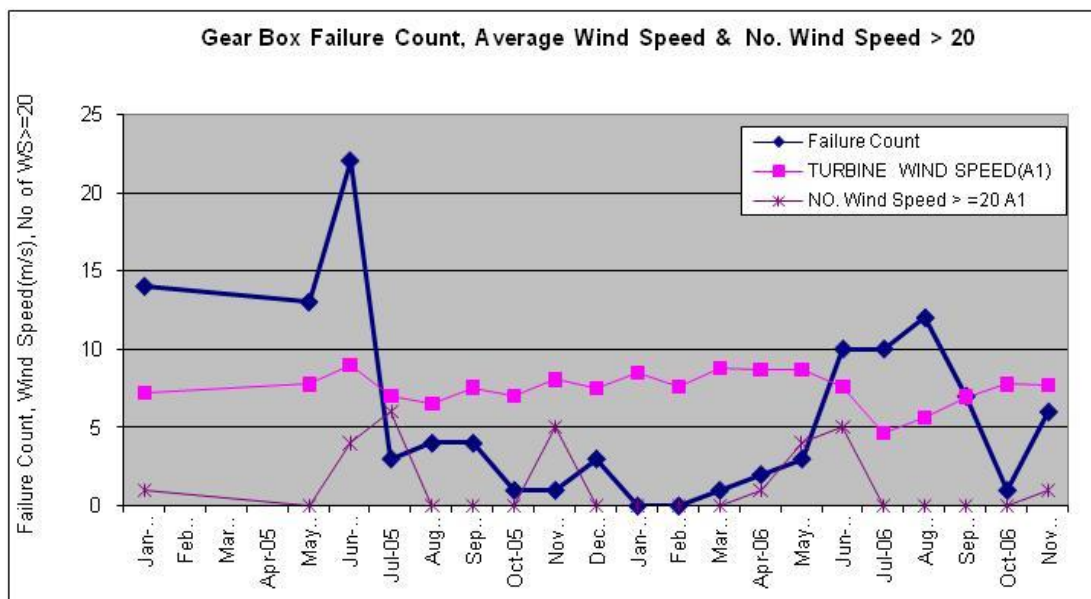


Figure 1 Developed wind turbine and wind farm availability models and studied effect of different parameters on wind turbine failure rates.

Coolen FPA, Spinato F and Venkat D, (2008) *On modelling of grouped reliability data for wind turbine*, IMA Journal of Management Mathematics, published online on July 11, 2008. Online access: <http://imaman.oxfordjournals.org/cgi/content/abstract/dpn012v1>

ABSTRACT

Energy generation by wind turbines has increased enormously during the last decade, and plans for future expansion, in particular large-scale off-shore developments, emphasize the need to study reliability of wind turbines. Substantial data sets on occurrences of failures in wind turbines are available, but unfortunately they only provide grouped data with little information on individual turbines or maintenance activities. In this paper, we consider the use of basic non-homogeneous Poisson process models, in particular the power-law process, to try to deduce from these data the change, through the years, in reliability of wind turbines and some critical subsystems. Unfortunately, it turns out that there are major problems that avoid clear conclusions to be drawn, as such the main contribution of this paper is a discussion on choice of the use of either calendar time or total-time-on-test as the key time variable in reliability models, and some advice on future data collection, which will be equally important for a range of industrial activities.

Guo H, Watson SJ, Tavner P and Xiang J, (2009) *Reliability analysis for wind turbines with incomplete failure data collected from after the date of initial installation*, Journal of Reliability Engineering and System Safety, Vol. 94, Issue 6, pp 1047-1063. Online access: <http://dx.doi.org/10.1016/j.ress.2008.12.004>

ABSTRACT

Reliability has an impact on wind energy project costs and benefits. Both life test data and field failure data can be used for reliability analysis. In wind energy industry, wind farm operators have greater interest in recording wind turbine operating data. However, field failure data may be tainted or incomplete, and therefore it needs a more general mathematical model and algorithms to solve the model. The aim of this paper is to provide a solution to this problem. A three-parameter Weibull failure rate function is discussed for wind turbines and the parameters are estimated by maximum likelihood and least squares. Two populations of German and Danish wind turbines are analyzed. The traditional Weibull failure rate function is also employed for comparison. Analysis shows that the three-parameter Weibull function can obtain more accuracy on reliability growth of wind turbines. This work will be helpful in the understanding of the reliability growth of wind energy systems as wind energy technologies evolving. The proposed three-parameter Weibull function is also applicable to the life test of the components that have been used for a period of time, not only in wind energy but also in other industries.

Smolders K, Long H, Feng Y and Tavner PJ, *Reliability analysis and prediction of wind turbine gearboxes*. EWEC2010, Scientific Track, Poster Presentation, Warsaw, 20th – 23th Apr 2010.

Online access: <http://www.supergen-wind.org.uk/publications.html>

This paper presents a reliability analysis model of wind turbine gearboxes by developing a generic gearbox configuration and modular structure. It encapsulates all the reliability critical components within the gearbox subsystem in a wind turbine. Reliability block diagrams of gearbox modules and components have been established by using Relx Reliability Analysis software. Failure rates of the critical components are estimated by applying existing industrial standards and datasheets for general mechanical applications. Results of failure rates and reliability of three generic gearbox configurations have been obtained. To improve the reliability prediction of wind turbine gearbox, an advanced prediction model based on failure modes and load carrying capability of individual components under operational conditions has been discussed. This research has highlighted the importance of validation of the reliability prediction models using available field failure data, which could be only possible through collaborations of wind farm owners, WT manufacturers, gearbox manufacturers, and bearing manufacturers.

Spinato F, Tavner P and van Bussel G, *Reliability-Growth Analysis of Wind Turbines from Fleet Field Data*, presented at AR2TS (Advances in Risk and Reliability Technology Symposium) Conference, Loughborough, April 2007.

Online access: <http://www.supergen-wind.org.uk/publications.html>

ABSTRACT

The availability of failure data for complex and commercially relevant systems, like wind turbines, is often restricted to a few publicly accessible databases, which collect failures in grouped form for entire fleets of units. Despite the deficiencies of this data, reliability-growth analysis methods do allow the extraction of reliability trends over an observed period. The analysis can also differentiate between

- subassemblies in a system subject to human-driven reliability improvement and mature technology
- subassemblies which are deteriorating, characterised by an increasing failure intensity.

For this purpose the Crow-AMSAA mathematical model, based on the Power Law Process (PLP), has been implemented on fleet failure data from wind turbines in Germany over a 10 year period. Better design, maintenance or repair activities will spread technological innovation throughout a fleet of systems with a rapidity that is reflected by the value of the shape parameter of the failure intensity function. This is demonstrated in the analysis of the wind turbine fleet failure data. In fleets or subassemblies with more static technology, analysis of the failure data should exhibit technology maturity. This is demonstrated in the analysis by the negative reliability growth encountered.

Two statistical tests were applied to the wind turbine data, the goodness of fit for the Power Law Process and the null hypothesis of constant intensity function for the same PLP, which is the Homogeneous Poisson Process (HPP). The results from the intensity function analysis were used to approximate the expected failure intensity for different designs of wind turbine and were subsequently compared with failure from other surveys to improve confidence in the validity of the analysis. The results from this type of wind turbine subassembly failure analysis can indicate the reliabilities which could be expected in the prospective off-shore installation of wind energy turbines, showing the wind turbine concepts which will offer a greater potential for reliability improvement in the future.

Spinato F, Tavner PJ, van Bussel, GJW and Koutoulakos E, (2009) *Reliability of wind turbine subassemblies*, IET Renewable Power Generation, Vol. 3, No. 4, pp. 387-401.

Online access: <http://dx.doi.org/10.1049/iet-rpg.2008.0060>

ABSTRACT

We have investigated the reliability of more than 6000 modern onshore wind turbines and their subassemblies in Denmark and Germany over 11 years and particularly changes in reliability of generators, gearboxes and converters in a subset of 650 turbines in Schleswig Holstein, Germany. We first start by considering the average failure rate of turbine populations and then the average failure rates of wind turbine subassemblies. This analysis yields some surprising results about which subassemblies are the most unreliable. Then we proceed to consider the failure intensity function variation with time for wind turbines in one of these populations, using the Power Law Process, of three subassemblies; generator, gearbox and converter. This analysis shows that wind turbine gearboxes seem to be achieving reliabilities similar to gearboxes outside the wind industry. However, wind turbine generators and converters are both achieving reliabilities considerably below that of other industries but the reliability of these subassemblies improves with time. The paper also considers different wind turbine concepts. Then we conclude by proposing that offshore wind turbines should be subject to more rigorous reliability improvement measures, such as more thorough subassembly testing, to eliminate early failures. The early focus should be on converters and generators.

Tavner PJ, Edwards C, Brinkman A and Spinato, F, (2006) *Influence of Wind Speed on Wind Turbine Reliability*, Wind Engineering, Vol. 30, No. 1, pp. 55-72.

Online access: <http://dx.doi.org/10.1260/030952406777641441>

ABSTRACT

Wind turbines have been erected in increasing numbers in Europe, the USA and elsewhere. In Europe Denmark has played a particularly prominent part in developing the technology and has installed a large numbers of turbines. The paper is concerned with the influence of the weather on the reliability of modern wind turbines and in particular the effect of wind speed. The prime objective of the work is to extract information from existing reliability data to draw conclusions about how the wind speed affects turbine reliability and which subassemblies in the turbine it affects the most. The purpose is to make information available to turbine manufacturers and operators so that the reliability of new wind turbine designs can be improved, particularly if they are to be installed offshore, where the weather is more inclement. Data are collected from Windstats for historic, maintained, Danish wind turbines and on-line data collected for the Danish weather. These data are used to analyse the reliability of wind turbines and their subassemblies in varying weather conditions from 1994-2004. The paper describes practical methods of extracting information from wind turbine reliability data and shows how turbine design, turbine configuration, time and the weather can affect the extracted results.

Tavner PJ and Spinato F, *Reliability of wind turbines*, UKERC Sustainable Energy UK:

Meeting the Science and Engineering Challenge, St Anne's College, Oxford, UK, 13th – 14th May 2008. Online access: <http://www.supergen-wind.org.uk/publications.html>

ABSTRACT

This paper investigates the reliability of more than 6000 modern onshore wind turbines and their subassemblies in Denmark and Germany over 11 years and particularly the changes in reliability of generators, gearboxes and converters in up to 650 wind turbines in Schleswig Holstein in Germany. It starts by considering the average failure frequency of the turbine populations and then goes on to consider the average failure frequencies of wind turbine subassemblies. This analysis yields some surprising results about which subassemblies are the most vulnerable. The paper then proceeds to consider the variation of failure frequencies with time of 3 subassemblies; generator, gearbox and converter, for wind turbines in one of these population, in Schleswig Holstein, Germany, using the Power Law Process. This analysis shows that wind turbine gearboxes seem to be achieving reliabilities similar to gearboxes outside the wind industry. However, wind turbine generators and converters are both achieving reliabilities considerably below that of other industries but the reliability of these subassemblies is improving with time. The paper concludes by proposing that offshore wind turbines should have their subassemblies tested more thoroughly than at present, particularly converters and generators, to eliminate early failures.

Tavner PJ, Spinato F, van Bussel GJW and Koutoulakos E, *Reliability of different wind turbine concepts with relevance to offshore application*, EWEC2008, Brussels, Belgium, 31st March – 3rd April 2008. <http://www.supergen-wind.org.uk/publications.html>

ABSTRACT

This paper investigates the reliability of more than 6000 modern onshore wind turbines and their subassemblies, ranging in size from 300-1800 kW, in Denmark and Germany over 11 years and particularly the changes in reliability of generators, gearboxes and converters in a subset of 650 of these wind turbines in Schleswig Holstein, Germany. The analysis yields some surprising results about which subassemblies are the most unreliable but stresses that Mean Time to Repair (MTTR) is also important. The paper then proceeds to consider the failure frequencies of subassemblies in direct and geared drive wind turbines in one German population.

This analysis shows that direct drive wind turbines do not necessarily have better reliability than geared drive turbines but do have better potential to improve their reliability with time. Wind turbine generators and converters are both achieving reliabilities considerably below that of other industries but the reliability of these subassemblies is improving with time. The paper concludes by considering the effect of wind turbine concept on reliability and its influence on future wind turbine concepts if they are to achieve the reliability performance needed offshore.

Tavner PJ, van Bussel GJW and Spinato F, *Machine and Converter Reliabilities in Wind Turbines*, 3rd International IEE Conference, Power Electronics Machines and Drives, Dublin, 2006. Online access: <http://www.supergen-wind.org.uk/publications.html>

ABSTRACT

Electrical Machine/Converter combinations are used in a variety of applications, from powers of Watts to MegaWatts. Some applications, such as propulsion and generation, have high reliability & availability requirements. Modern large wind turbines incorporate variable pitch blades and a variable speed Generator, which feeds the Grid through a Converter and have a need for high reliability & availability. There are a number of configurations of generator and converter intended to provide optimum performance for present and future wind power. This paper describes an investigation into the reliabilities of Generators and Converters in such configurations and is based on failure data collected in Germany and Denmark. The paper draws conclusions about which configurations have the higher reliability and identifies the subassemblies of the turbines which require attention for the future design of high reliability wind turbines. Recommendations are made about how designers and operators of wind turbines can increase their reliability by the choice of Concept and the operating regime.

Tavner PJ, Xiang J and Spinato F, (2007) *Reliability Analysis for Wind Turbines*, *Wind Energy*, Vol. 10, pp. 1-18. Online access: <http://dx.doi.org/10.1002/we.204>

ABSTRACT

Modern wind turbines are complex aerodynamic, mechanical and electrical machines incorporating sophisticated control systems. Wind turbines have been erected in increasing numbers in Europe, the USA and elsewhere. In Europe, Germany and Denmark have played a particularly prominent part in developing the technology, and both countries have installed large numbers of turbines. This article is concerned with understanding the historic reliability of modern wind turbines. The prime objective of the work is to extract information from existing data so that the reliability of large wind turbines can be predicted, particularly when installed offshore in the future. The article uses data collected from the Windstats survey to analyse the reliability of wind turbine components from historic German and Danish data. Windstats data have characteristics common to practical reliability surveys; for example, the number of failures is collected for each interval but the number of turbines varies in each interval. In this article, the authors use reliability analysis methods which are not only applicable to wind turbines but relate to any repairable system. Particular care is taken to compare results from the two populations to consider the validity of the data. The main purpose of the article is to discuss the practical methods of predicting large-wind-turbine reliability using grouped survey data from Windstats and to show how turbine design, turbine configuration, time, weather and possibly maintenance can affect the extracted results.

Watson SL and Guo H, *Wind Turbine Availability Analysis*, SUPERGEN Wind project report, DW1.3: Report on Availability of Onshore and Offshore Wind Turbines. Online access: <http://www.supergen-wind.org.uk/members/members.html>

ABSTRACT

This report presents a summary of research on wind turbine availability carried out by CREST, Loughborough University. The research is based on mathematical analysis of the data. Firstly, the data available for this work are introduced namely: data from the Ardrossan wind farm, the Brazos wind farm, German LWK and WMEP data. Then, the mathematical theory behind the availability analysis is discussed. The technique is applied to the Ardrossan and LWK data and the theoretical results are compared with actual data. An analysis of weather dependence on gearbox failure rate is also presented. Finally, conclusions and recommendations are given.

Wilkinson MR, Spinato F, Knowles M and Tavner PJ, *Towards the zero maintenance wind turbine*, 41st Universities Power Engineering Conference, Newcastle, UK, 6th – 8th September, 2006, pp. 74-78. <http://www.supergen-wind.org.uk/publications.html>

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.

Turbine instrumentation, measurement and data processing

As wind farm development continues to accelerate and grow in capacity, and particularly with the anticipation of moving offshore, a detailed understanding of individual turbine characteristics is necessary. SCADA data, whilst useful for operation and control, often does not contain information that can diagnose, or indeed predict, faults or failures. Much higher resolution, and much more comprehensive, data regarding the operation and behaviour of the turbine is necessary to improve design, control and reliability. This work has designed a bespoke PC based high speed (20kS/s), multi-channel data acquisition (DAQ) system that is to be installed in November 2009 on a ScottishPower owned Vestas V47 turbine at Harehill wind farm. The design of this system has been reported in two conference papers.

This DAQ system records the data into 3 simultaneous MySQL databases, and will record approximately 1TB of data, operating on recording 13 continuous hours of data per day, over the period of one month. This high quality operational data will form the basis of the development for a condition monitoring system that will be utilised in conjunction with SCADA data (both current and historical) to help trend machine performance, and establish operational limits. The DAQ system employs a nacelle mounted PC and acquisition boards to monitor: vibration (generator, gearbox and nacelle); temperature (gearbox, generator, external air and nacelle internal); generator power (voltage and current); yaw direction; pitch angle; wind speed; external humidity; external air pressure. This data is communicated to a tower base mounted secondary PC system via an optical fibre communications cable running down the tower, and recorded onto external hard drives that are manually swapped (for data retrieval) every month.

Swiszczy G, Cruden A, Booth C and Leithead WE, *A data acquisition platform for the development of a wind turbine condition monitoring system*, Int. Conf. on Condition Monitoring and Diagnosis, Beijing, China, 21st – 24th April 2008.

Access online: <http://www.supergen-wind.org.uk/publications.html>

ABSTRACT

Often condition monitoring (CM) system developers use simulation or test rig data due to a lack of actual wind turbine measurements however, this data may not necessarily reflect processes happening in the real turbine application. In order to determine different patterns of machinery deterioration, precise data of existing parameters at higher sampling frequencies up to 20 kHz is needed. Additional parameters, not currently commonly monitored, like turbine vibration or tower movement, are also desired. In this paper the design of a data acquisition (DAQ) platform to be mounted on a 660kW Vestas V47 wind turbine is presented. The requirements and limitations of the data acquisition application are discussed. A detailed explanation of the data acquisition program developed in LabVIEW as well as the possibilities for remotely controlling this process are given. Finally, different methodologies for handling, storing and accessing large volumes of data are presented with the authors' optimal solution highlighted.

Watson SJ, Infield DG, Barton JP and Wylie SJ, (2007) *Modelling of the performance of a building-mounted ducted wind turbine*, Journal of Physics: Conference Series 75 pp. 1-10.

Access online: <http://www.supergen-wind.org.uk/publications.html>

ABSTRACT

This paper presents computational fluid dynamics (CFD) modelling of the performance of a building-mounted ducted wind turbine. A resistive volume within the duct is used to represent a cross-flow turbine and different diffuser geometries have been investigated. A comparison is made between the power performance ratio of such a building-mounted ducted wind turbine rotor predicted by CFD calculations and those predicted on the basis of one-dimensional (1D) theory. Good agreement is seen between the two approaches for a freestanding duct but deviations are seen for the building-mounted case for the calculated power performance ratio apparently due to asymmetry in the flow profile entering the duct and the flow geometry around the combination of building and duct.

Zaher A, Cruden A, Booth C, Leithead W, *Database Management for High Resolution Condition Monitoring of Wind Turbines*, 44th International Universities Power Engineering Conference (UPEC2009), Glasgow, Scotland, 1st – 4th September 2009.

Access online: <http://www.supergen-wind.org.uk/publications.html>

ABSTRACT

Wind turbine condition monitoring (CM) is an area of research which has been receiving a large amount of attention in the recent years. This has been influenced mainly by the recent uptake of wind farms being installed around the country. Operational and maintenance expertise in the area of wind turbine CM is therefore seen to be of growing importance but is yet to be well established in the industry due to its unverified economic benefits. The majority of the research which can be found in the literature has been based on simulation or test rig data, often due to the lack of availability of extensive historical data sets containing 'interesting' events, as well as the difficulties associated in gaining access to such data, due to its commercially sensitive nature. It can not be readily claimed, nor shown that laboratory based testing or simulations actually reflect real turbine operation, due to scaling, control and dynamic considerations. In order that different patterns of machine deterioration can be determined and detected in their incipient stages, precise high resolution data, of existing monitored parameters, should be sampled at frequencies higher than that is typically available in the integrated SCADA systems installed in most modern turbines today. This paper reports the design of a data acquisition platform which will be mounted on a 660kW VESTAS V47 wind turbine. Details of the monitoring equipment used, the installation requirements as well as the system architecture will be presented and discussed.

Turbine configuration

Two wind turbine exemplar turbines of 2MW and 5MW are defined in this topic, with configuration for future large scale off-shore machines.

Leithead WE and Watson S, (2009) *Exemplar Turbines for SUPERGEN*, SUPERGEN Wind project report, DW.2.1: Report on Current and Possible Future Wind Turbine Configurations. <http://www.supergen-wind.org.uk/members/members.html>

ABSTRACT

There are a large number of possible wind turbine configurations. The basic options are constant speed stall regulated, constant speed pitch regulated, variable speed stall regulated and variable speed pitch regulated. Because of the size of the wind turbines for offshore deployment, both constant speed operation and stall regulation would present considerable challenges to realising. The option for the immediate future is thus likely to be the variable speed pitch regulated configuration. Several different drive-train configurations are considered; indirect drive with a gearbox and conventional generator, direct drive with a multi-pole generator and semi-direct drive with a single stage gearbox and generator. The potential advantage in terms of reliability of the direct drive system is noted. However, the failure rate analysis of Theme W indicates that historically this has not been realised, although the experience with recent Enercon wind turbines is encouraging. The disadvantages are their large size and weight. For offshore deployment, these factors together with the need for heavy lift vessels, when undertaking repairs, can impact severely on the turbine availability. In a study of this issue, it was found that there was a strong site sensitivity indicating that direct drive might not be the best option for some far offshore sites.

The option of reducing the complexity of the wind turbines is considered. One possibility is to locate part or some of the power electronics for a small group of wind turbines at a central hub. The local power network would be operated with variable frequency thereby giving the wind turbines a reduced variable speed capability. The reduction in the controllability of the wind turbines together with the vulnerability to faults in the central hub power electronics mitigates against this approach.

Following on from the above arguments, it has been decided that the SUPERGEN Wind exemplar wind turbines are variable speed pitch regulated three-bladed machines with a conventional indirect drive. Two exemplar machines are defined, a 2MW and a 5MW offshore wind turbine. Full bladed models of these wind turbines are available and have been used through the work of the Consortium. A description of these two machines is in Exemplar wind turbines.

Dominguez S and Leithead WE, *Size related performance limitations on wind turbine control performance*, Proc. Control 2006, Glasgow, 2006.

Online access: <http://www.supergen-wind.org.uk/publications.html>

ABSTRACT

Wind turbine size has increased exponentially for the last twenty years. With the increase in size the control systems for variable speed pitch regulated machines play a greater role, since they are used for other tasks than just regulating generator speed. The structural dynamics impact directly on the achievable control system performance becoming more restrictive as the size of wind turbine increases. To make this dependence explicit, the relationships between performance measures of the control system and wind turbine structural dynamic characteristics are derived.

Wake development & interactions

The performance of a wind turbine and the imposed loads depend critically upon the wind-flow characteristics of the atmospheric boundary layer (ABL) – mean shear and turbulence – and the wakes of upstream machines. The turbulence characteristics and the mean shear in the ABL is controlled by the presence of stable/unstable stratification, surface roughness and, for onshore machines, ground topography. Stable stratification generally leads to high mean shear and low turbulence, and slower decay of the wakes than in neutral flow, while unstable stratification leads to the opposite – higher turbulence, lower mean shear and more rapid wake decay. Periods of stable stratification occur at wind speeds large enough for significant power generation. The rate at which the wakes develop controls the minimum permissible spacing between turbines and hence the number of turbines in a given area, and impinging mean shear and turbulence affects the design of wind turbine rotors as blades become relatively thinner. These factors will be more significant for the new generation of large machines and current prediction tools (historically based on small machines in assumed neutral conditions) are already becoming inadequate. There is therefore an urgent need for new and improved tools.

Three conference papers and two deliverable reports and were produced in this topic.

Pascheke F and Hancock, PH, *Wake development and interactions within an array of large turbines*, European Wind Energy Conference (EWEC2008), Brussels, 31st March – 3rd April 2008. Online access: <http://www.supergen-wind.org.uk/publications.html>

ABSTRACT

This paper presents first test results from wind tunnel studies of mean and turbulent wake characteristics within an array of large wind turbines. Up to now, a single rotating speed controlled 1:300 scale model of a 5MW-rated machine with a rotor diameter of 126m and a hub height of 90m is tested in a realistic model off-shore atmospheric boundary layer. The blade design is based on blade-element theory for low Reynolds number blade aerodynamics to comply with modelling requirements. Preliminary tests in a low-turbulence flow at a tip speed ratio of TSR=6 yielded a thrust coefficient of $CT=0.52$ which is within 5% of the predicted value of the theoretical design case with a lift coefficient of $CL=0.6$ (but a larger blade chord to mimic a higher CL). Velocity measurements in the modelled off-shore boundary layer at several downstream positions suggest a transition from near to far wake at a downstream distance of approximately 4 rotor diameters D . At a downstream distance of 10D turbulence intensities in the wake of the single model turbine are still approximately twice as large as in the undisturbed boundary layer. Along with the high turbulence levels a velocity deficit of about 25% is found. Time averaged flow fields and lateral profiles of the vertical velocity clearly illustrate the characteristic swirl generated by the blade rotation, which persists until about a downstream distance of 7D.

Pascheke F and Hancock PE, *Wake development and interactions within an array of large wind turbines*, The International Workshop on Physical Modelling of Flow and Dispersion Phenomena (PHYSMOD 2007), University of Orleans, France, 29th – 31st August 2007. Online access: <http://www.supergen-wind.org.uk/publications.html>

ABSTRACT

The investigation of wake development and wake interactions within an array of large wind turbines is a key objective in the EnFlo Wind tunnel laboratory contribution to the SUPERGEN V - Wind Energy Technologies project. Extracting energy from the wind, the turbine wake is generally characterised by reduced wind speeds and increased levels of turbulence. Within a wind farm array, the effects of several wakes interact. Thus, the turbines produce less energy and stand greater structural loads than single turbines placed in the free stream (see e.g. Burton et al. (2002); Vermeer et al. (2003)). Current prediction models need improving for these large machines.

Two primary mechanisms determine the decrease of momentum deficit in the wake of a wind turbine: mechanical turbulence generated by the turbine itself, which is controlled by the turbine design and performance and usually is of a relatively high frequency and small scale, and the turbulence level in the ambient atmospheric boundary layer (ABL) flow. With the latter being controlled by terrain roughness, topography, stratification, etc., the characteristic length scales as well as spectral characteristics of these two interacting mechanisms are quite different. Moreover, the quantitative effect of the interactions change as rotor size increases.

Wake characteristics, development and interactions will be studied in the large EnFlo wind tunnel (L x W x H : 20 x 3.5 x 1.5 m) for two different machine sizes: 5 MW with a rotor diameter of 126 m and a hub height of 90 m and 2 MW with a rotor diameter of 75 m and a hub height of 65 m. At a model scale of 1:300 up to five 5 MW model turbines (eight 2 MW machines respectively) will be arranged successively in the test section as shown in Figure 1. The planned case studies comprise off-shore ABLs for neutral and nonneutral conditions as well as a rural neutrally stratified ABL over different terrain (from flat to steep). The wake measurements will be made using LDA, including phase-locked measurements to separate ordered motion from genuine turbulence.

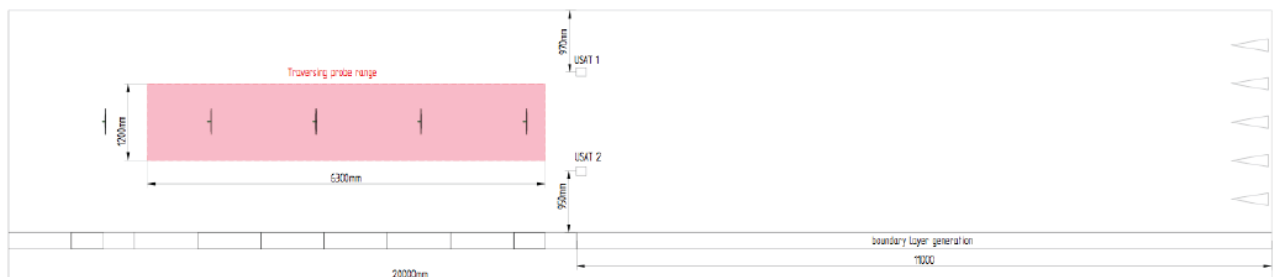


Figure 1: Model set-up for the 5 MW turbine array (topview). Flow from right to left, shaded area indicates the probe traversing range.

Pascheke F and Hancock PE, *Influence of ABL characteristics on wind turbine wakes: surface roughness and stratification*, PHYSMOD 24th – 26th August, Sint-Genesius-Rode, Belgium, 2009. Online access: <http://www.supergen-wind.org.uk/publications.html>
 ABSTRACT

Extracting energy from the wind, the wind turbine wake is generally characterised by reduced wind speeds and increased levels of turbulence. Within a wind farm array, the effects of several wakes interact resulting in reduced power generation and increased fatigue loads. Two primary mechanisms determine the decrease of momentum deficit in the wake of a wind turbine: mechanical turbulence generated by the turbine itself, which is controlled by the turbine design and performance and usually is of a relatively high frequency and small scale, and the turbulence level in the ambient atmospheric boundary layer (ABL) flow. With the latter being controlled by terrain roughness, topography, stratification, etc., the characteristic length scales as well as spectral characteristics of these two interacting mechanisms are quite different.

Wake characteristics, development and interactions are studied in the large EnFlo wind tunnel (L x W x H : 20 x 3.5 x 1.5 m) at a model scale of 1:300 for a 5 MW machine with a rotor diameter of 126 m and a hub height of 90 m. Completed case studies comprise the comparison of wake development in o_-shore and rural ABLs for neutral conditions (Figure 1) as well as wake interactions for small farm arrays (maximal 3 turbines) in neutral off-shore conditions.

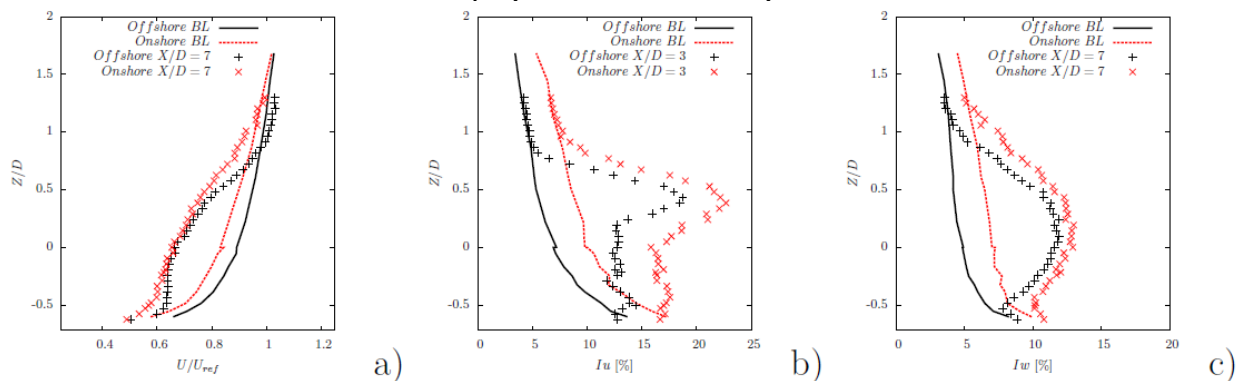


Figure 1: Comparison of wake development in o_-shore and rural neutral stratified ABLs.

Vertical profiles of a) mean wind, b) longitudinal and c) vertical turbulence intensities.

Neutral stability is usually considered to be the most important situation for wind energy applications, particularly with respect to turbulent wind loads on the turbine in strong winds. Nevertheless, in unstable conditions large convection cells (thermals and plumes) develop and may cause sudden gusts at low levels. While strong wind shear is found in the surface layer, changes of mean wind speed with height are small above heights of 100m due to increased vertical mixing and transfer of momentum. In stable conditions, turbulence is suppressed affecting the wind speed recovery in a turbine wake. Furthermore, the increase of wind speed with height can be large. Wind turbines are thus subject to significant asymmetric loading due to high wind shear. Non-neutral ABL conditions play a role in both on- and off-shore wind farming. Over land stability variations show a daily cycle while off-shore conditions tend towards a season cycle with unstable conditions in fall-winter and stable conditions in spring-summer. However, the average stratification in mid-latitudes is slightly stable. Wind tunnel studies on the influence of stratification on the wake development will commence soon and preliminary results will be presented in addition to the roughness case studies.

Pascheke F and Hancock P, (2009) *Wind Tunnel Atmospheric Boundary Layer Simulation for the SUPERGEN V – Wind Energy Technologies Project*, DW.3.1 Wind-tunnel simulation of large wakes in various ABL conditions, SUPERGEN Wind Technologies. Access online: <http://www.supergen-wind.org.uk/members/members.html>

INTRODUCTION

The investigation of wake development and wake interactions within a wind farm array is a key objective in the EnFlo contribution to the SUPERGEN Wind. Extracting energy from the wind, the turbine wake is characterised by reduced wind speeds and increased levels of turbulence. Within a wind farm array, where the effects of several wakes interact, turbines therefore produce less energy and can be subjected to greater structural loads than single turbines placed in the free stream.

As the wake convects downstream, strong wind speed gradients between the reduced wind speed of the wake and the free flow outside of the wake result in additional shear generated turbulence enhancing the momentum transfer from the free flow into the wake region. The wake width increases due to the mixing and the momentum deficit reduces until the flow is fully recuperated far downstream. The turbine itself additionally generates mechanical turbulence (shedding of tip vortices, and general disturbance of the flow caused by the turbine structure, so that two primary factors determine the decrease of the momentum deficit in the wake: the turbulence generated by the wake itself (controlled by the turbine design and usually of relatively high frequency) and the turbulence level in the ambient atmospheric boundary layer (ABL) flow (controlled by surface roughness, topography, stratification, etc.). The characteristic length scales as well as the spectral characteristics of these two interacting mechanisms are quite different and since one relates to the turbine configuration, the quantitative effect of the interactions change as rotor size increases.

The work packages for the study of wake development and Interactions contain

- Wake development and interactions in off- shore ABLs for neutral, stable and unstable conditions.
- Wake development and interactions in the on-shore ABL over various terrain (up to three cases).

Wake characteristics, development and interactions will be studied in the large EnFlo wind tunnel (L×W×H : 20 × 3.5 × 1.5 m) for a 5MW machine size with a rotor diameter of 126 m and a hub height of 90 m. At a model scale of 1:300 four to five model turbines will be arranged successively in the test section. The measurements of wake development will be made using LDA, including in due course phase-locked measurements to separate ordered motion from genuine turbulence.

Preliminary wind tunnel experiments are conducted to generate model boundary layers with characteristic mean and turbulent properties at the appropriate model scale for the above mentioned test cases. The on-shore neutral stratification boundary layer was the first to be generated in the large EnFlo wind tunnel and will be documented in this short report.

Pascheke F and Hancock P, (2009) *Model wind turbines in the SUPERGEN V – Wind Energy Technologies Project*, DW.3.1 Wind-tunnel simulation of large wakes in various ABL conditions, SUPERGEN Wind Technologies.

Access online: <http://www.supergen-wind.org.uk/members/members.html>

INTRODUCTION

The EnFlo work packages within the SUPERGEN V – Wind Technologies project comprise the investigation of wake development and wake interactions within an array of wind turbines. The wake characteristics, development and interactions are being studied in the large EnFlo atmospheric boundary layer wind tunnel shown in Figure 1.1. The meteorological wind tunnel is an unique facility with comprehensive inlet flow and surface heating and surface cooling systems designed for the generation of neutral, stable and unstable boundary layers and neutral and stable free flows. Depending on the individual boundary layer set-up, wind speeds ranging from 0.3 to 4.5 ms⁻¹ can be realised.

The wind tunnel working section is $L \times W \times H$: 22 m \times 3.5 m \times 1.5 m. For a 5MW machine with a rotor diameter of 126 m and a hub height of 90 m a model scale of 1 : 300 has been chosen to ensure sufficient spatial resolution for the wake measurements. Allowing for reasonable longitudinal spacing of 6 – 8 rotor diameters D up to five rotating, speed controlled scale model wind turbines will be arranged successively in the test section. Wake interactions of 2 – 3 parallel turbines with a lateral spacing of 3 – 4 D will also be studied.

The case studies comprise off-shore atmospheric boundary layers (ABLs) for neutral and non-neutral conditions, as well as a rural neutrally stratified ABL over different terrain.

Up to now, the neutral on- and off-shore ABL's have been developed. A comprehensive documentation of the respective modelled ABL characteristics is given in the previous report. The experimental programme includes phase locked wake turbulence measurements to separate ordered motions from ABL and blade generated turbulence.

Naturally, phase locking analysis requires the tip speed ratio to be constant within reasonable limits. This report documents the performance of three different motor controls which were tested in uniform, low turbulence flow and in a highly turbulent model boundary layer.

Effect of forest canopies

A number of wind farms are now being sited in less ideal places including close to forests. The forest canopy can significantly change the wind shear profile and increase turbulence levels. Both of these factors will have a significant impact on the design of large wind turbines. The effect of the forest canopy on the wind speed profile is not fully understood and several numerical techniques have been used to model the effect of the forest canopy.

The application of a computational fluid dynamics (CFD) code, simulating the effect of the forest canopy as a porous resistive element has shown to produce promising results. This work will be extended by experimenting with a number of different resistive elements types, sizes and porosities to simulate different canopy types. The results from these simulations will be validated against field data from E.ON.

The following papers detail some early results from CFD modelling of a forest canopy and comparison with wind tunnel measurements.

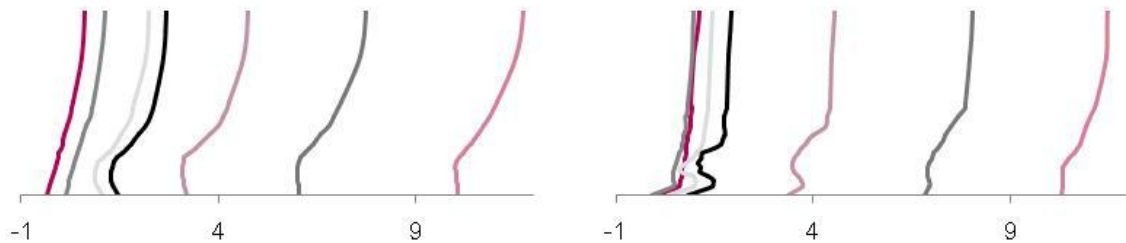


Figure 2 Validated CFD models of forest canopies against wind tunnel scale measurements.

Soler-Bientz R, Watson SJ and Infield DG, *Study of the offshore wind and its propagation inland of the northern zone of the Yucatan Peninsula, Eastern Mexico*, EWEC2009, Marseille, France, March 2009. <http://www.supergen-wind.org.uk/publications.html> ABSTRACT

A preliminary study of the wind characteristics of the northern zone of the Yucatan Peninsula, Eastern Mexico was undertaken for offshore and coastal sites using data measured from three measurement sites. Ten minutes averages of wind speeds, wind directions and ambient temperatures at two different heights were recorded from data measured over a year. The usual wind statistics analysis was undertaken to evaluate the atmospheric stability and the relation between the offshore and onshore winds. The results were compared with the models previously proposed by Monin-Obukhov and by Hsu.

Wylie SJ and Watson SJ, *Computational Fluid Dynamics (CFD) Modelling of Wind Flow in and around Forest Canopies*, 5th PhD Seminar on Wind Energy in Europe, Durham, 30th Sep – 1st Oct 2009. Online access: <http://www.supergen-wind.org.uk/publications.html> ABSTRACT

Using the well known k- ϵ turbulence model, a CFD study has been carried out and compared to a wind tunnel study to assess its accuracy in modelling wind flow through and around a forest canopy. Adding additional source and sink terms to the turbulence model, has been common practice when taking into account the effect of trees on the approaching wind field. This research is looking at four different sets of closure coefficients, which define the source and sink terms, to see which can most accurately simulate the wind tunnel study.

Wylie SJ, Watson SJ and Infield DG, *Modelling the output of a flat-roof mounted wind turbine with an edge mounted lip*, European Wind Energy Conference (EWEC2008), Brussels, Belgium, 31st March – 3rd April 2008.

Online access: <http://www.supergen-wind.org.uk/publications.html>

ABSTRACT

This paper presents a computational fluid dynamic (CFD) simulation of the wind flow over a flat roof with and without an aerodynamically shaped lip on the leading edge of an isolated building. The intention is to show the advantage of mounting a relatively inexpensive aerodynamically shaped lip on the building to delay flow separation so that a roof mounted wind turbine can benefit from the accelerated wind over a flat roof building without having to be mounted on a relatively high mast outside of the flow separation region immediately above the roof surface. By altering a hypothetical rotor's resistance, a comparison of extracted power against the theoretical power available to the rotor will be made. From the simulations it can be seen that placement of an aerodynamically shaped lip on the buildings leading edge does increase power extraction from the theoretical turbine rotor, by 7% at its maximum. By increasing the amount of rotor resistance it can be seen that this can inhibit flow separation at the building's leading edge and increase wind speeds through the rotor of up to 15% and hence the power available to the rotor is increased. Although the results from this work are positive, more detailed analysis is needed into the aerodynamic optimisation of the lip shape and rotor placement.

Wylie SJ, Watson SJ and Searight T, *Computational Fluid Dynamics Modelling and Validation of Wind flow over a Forest Canopy*, EWEC2009, Marseille, France, March 2009.

Online access: <http://www.supergen-wind.org.uk/publications.html>

ABSTRACT

Some wind farms are now being sited in less ideal places, including in and around forests. The forest canopy can significantly alter the wind shear profile and reduce the overall resource available, as well as increasing turbulence levels. This paper will present a computational fluid dynamics (CFD) simulation of the wind flow over a small forested region, Hill Holt Wood, in Lincolnshire, UK. The intention is to show that accurate modelling of wind flow over a forest can be achieved for a relatively small forest but attention must be paid to variation in canopy density for accurate results.

The added complexities of forests and forest canopies on the incoming wind profile is still an area of uncertainty in the wind energy sector. For many reasons wind farm developers are having to look at erecting wind farms in less than ideal terrain types, including in and around forest canopies. Past work has shown that forest canopies will reduce the total wind resource seen at the site as well as increasing the amount of turbulence, which are undesirable characteristics for erecting a wind farm. If a better understanding of the canopy effects can be achieved this could help when erecting wind farms in the vicinity of forest canopies. It will help in producing more accurate predictions of a site's total available wind resource and allow for more efficient turbine design and siting in this type of terrain. Due to the difficulty in getting accurate measurements from many forested regions, as with many other complex sites, a computational fluid dynamics (CFD) model, CFX11, is used for this work. CFD provides a mechanism to gain an insight into the wind conditions over a large volume at a site which would not be feasible by measurement alone provided that there is a sufficiently accurate understanding of the physics and fluid behaviour. This work compares measured data from a site at Hill Holt Wood, Lincolnshire, UK, with CFD modelling of the wind profile at the site. The CFD simulations are based on the idea of modelling a forest as a resistive porous volume. The results highlight the sensitivity of the predicted wind speed values to the porosity which is assigned to the variation in canopy coverage with height, particularly where the height of interest is close to the canopy top. This emphasises the importance of modelling the canopy in layers to simulate the effect of varying leaf density with height, particularly where the density of trees is quite small.

Other publications

Tavner PJ, Ran L, Penman J and Sedding H, *Condition Monitoring Of Rotating Electrical Machines*, IET, Stevenage, ISBN 978-0-86341-741-2, 2008.

[http://books.google.co.uk/books?id=s-](http://books.google.co.uk/books?id=s-1T1fxK4QEC&dq=peter+tavner&lr=&source=gbs_navlinks_s)

[1T1fxK4QEC&dq=peter+tavner&lr=&source=gbs_navlinks_s](http://books.google.co.uk/books?id=s-1T1fxK4QEC&dq=peter+tavner&lr=&source=gbs_navlinks_s)

Book Preface (first two paragraphs)

Condition monitoring of engineering plant has increased in importance as more engineering processes become automated and the manpower needed to operate and supervise plant is reduced. However, electrical machinery has traditionally been thought of as reliable and requiring little attention, except at infrequent intervals when the plant is shut down for inspection. Indeed the traditional application of fast-acting protective relays to electrical machines has rather reduced the attention that operators pay to the equipment.

Rotating electrical machines, however, are at the heart of most engineering processes and as they are designed to tighter margins there is a growing need, for reliability's sake, to monitor their behaviour and performance on-time. This book is a guide to the techniques available. The subject of condition monitoring of electrical machines as a whole covers a very wide field including rotating machines and transformers. To restrict the field the authors deal with rotating machines only and with techniques that can be applied when those machines are in operation, neglecting the many off-line inspection techniques.

A first edition of *Condition Monitoring of Electrical Machines*, written by Tavner and Penman, was published in 1987. The economics of industry have now changed, as a result of the privatisation and deregulation of the energy industry, placing emphasis on the importance of reliable operation of plant, throughout the whole life cycle, regardless of first cost. The availability of advanced electronics and software in powerful instrumentation, computers, and digital signal processors (DSP) has simplified our ability to instrument and analyse machinery. As a result condition monitoring is now being applied to a wider range of systems from fault-tolerant drives of a few hundred watts in the aerospace industry, to machinery of a few hundred megawatts in major capital plant.

In this new book the original authors have been joined by Ran, an expert in power electronics and control, and Sedding, an expert in the monitoring of electrical insulation systems. Together the authors have revised and expanded the earlier book, merging their own experience with that of machine analysts to bring it up to date.

4.3 Theme X: Drive-train loads and monitoring

Theme leader: Durham University

Partners: Durham University
Loughborough University
Manchester University
Rutherford Appleton Laboratory
University of Strathclyde

4.3.1 Introduction

Most models design of wind turbines are used for assessing loads and control strategies and have not really been designed primarily for fault detection. One objective of this section of work will be to develop a model of the turbine specifically for the simulation of fault conditions and how these conditions are likely to manifest themselves in the available sensor data.

From an operational prospective, the availability of a wind turbine or a wind farm must be optimised to maximise revenue. To achieve this goal, an intelligent condition monitoring system must be specified which is capable of monitoring the health of a wind turbine by measuring the appropriate signals, analysing the data, providing advice to operators and possibly taking corrective action to avoid or reduce further damage to components in order to allow the minimum required amount of maintenance within scheduled time windows. Present day turbines do have SCADA systems which monitor the performance of the turbine and alarms can be set which allow shut-down of the turbine under given conditions. However, the level of condition monitoring is fairly rudimentary examining for example, vibration levels, oil pressures, etc, in isolation and shutting the machine down when a certain fixed alarm level is reached. In many cases, remedial action far in advance, may avoid a total shut-down. To do this requires a condition monitoring system with further intelligence, i.e. one that can set varying alarm levels depending on the operating conditions, and one that can analyse multiple signals and compare them with known failure signatures. Such a system can then provide a more informed picture of the health of a turbine and suggest appropriate remedial action or schedule the required type of maintenance. Therefore, another objective of this section is to specify an integrated Condition Monitoring system, to allow effective operation and maintenance of wind turbines in the onshore and offshore environments

4.3.2 Research outputs

The research outputs are grouped by two research topics in this theme: Turbine characterisation and Condition monitoring system.

Turbine blade, electrical and mechanical characterisation

Condition monitoring and/or non-destructive testing of wind turbine blades is relevant both to the certification testing of blades in the laboratory, identification of manufacturing flaws, and the operation of wind turbines in the field.

In the laboratory, techniques are required to give the designer more detailed feedback of the stress distribution within the blade, to identify points of potential weakness, and to provide early warning of incipient failure so that key areas can be monitored more intensely. The current state of the art is to use an array of strain gauges which work well during a static test but are subject to failure during a fatigue test. Optical fibre strain gauges (sometimes embedded) are now being introduced, but like strain gauges they still only provide point measurements. Full field stress or strain measurement methods facilitate comparison with finite element blade models. Thermoelastic stress analysis is one such technique, but previous applications have suffered from the difficulty of interpreting the measured data.

In the field, operators rely on visual inspection and physical tapping of the surface to identify potentially weakened areas, but there is currently no comprehensive and reliable way to assess blade integrity. This is likely to be increasingly a problem for offshore wind turbines where design margins may be tighter and access for inspection and maintenance is difficult.

Blade modelling can assist in the appropriate location of sensors, the interpretation of measurements, and the assessment of damage criticality.

This research topic details the application of the parametric finite element blade model developed by STFC Rutherford Appleton Laboratory to interpret blade test measurements. In particular, the model has been used to:

- (i) Investigate the thermoelastic stress distribution developed at the surface of a blade containing a manufacturing flaw during bend testing; the results show good correlation of actual measurements on a sound blade and one with an introduced defect, allowing future interpretation of the levels of damage detectable by thermoelastic stress analysis.
- (ii) Assess the load distribution introduced into the blade by the novel dual-axis resonant load mechanism developed by NaREC (New and Renewable Energy Centre) for their full-scale test facility, compared to that seen by in-service blades, allowing comparison of the load introduction to the more standard single-axis method and how it affects load margins at different locations.

The research in electrical characteristics topic resulted in 6 journal and conference papers which describe the development of a full coupled-circuit electrical DFIG generator model and the validation of this model on the electrical DFIG test rig at Manchester. The model is capable of accommodating any combination of the stator and rotor winding faults/imbalance and/or any rotor or stator voltage excitation unbalances. The model has also been used to investigate the effects of voltage unbalance on DFIG operation in terms of increased losses (ie heating effects) and pulsating torques (ie torsional resonances). The model results have been validated carefully on the DFIG test rig. The main output from the model has been a clear and unambiguous definition of the link between DFIG faults and the corresponding frequency components produced in the current (and power) spectra.

The research in mechanical characteristics topic resulted in 8 Journal and Conference Papers which describe the development and use of a Wind Turbine Condition Monitoring Test Rig developed at Durham University to investigate and trial methods of detecting mechanical and electrical faults on direct drive and indirect drive wind turbines. The Test Rig is driven by a variable speed DC motor the Converter for which can simulate a variety of wind speed and turbulence conditions. The Converter is driven by a voltage proportional to speed derived from a wind turbine mechanical model developed by Strathclyde University which can be operated at a variety of wind speed and turbulence conditions.

Bonnet P, Dutton G, Court R, Ridley S, Jones H and Hope P, *Towards a more realistic fatigue loading for laboratory testing of wind turbine blades*, EWEC2009, Marseille, France, March 2009. Online access: <http://www.supergen-wind.org.uk/publications.html>

ABSTRACT

A novel procedure for conducting wind turbine blade fatigue testing is investigated. It features simultaneous loading in the main two directions: flapwise and edgewise; and uses the blade natural frequencies to force cyclic fatigue loads. This experimental scheme is modelled and studied with a finite element approach, using a full 3D blade model. Experimental strain distribution outputs are used to validate the model. The simulations are then used to examine the performance and relevance of the dual-axis test method for wind turbine blades.

Fatigue testing of wind turbine blades provides extremely valuable data for both blade manufacturers and turbine end-users in terms of design validation and certification for in-service requirements. However, existing tests using only one loading direction at a time are a gross simplification of the fatigue experienced by blades in service. To address this, NaREC has created a new technology whereby a blade can be loaded in two axes simultaneously, using a hydraulically powered resonance actuation system. This creates a test where the blade experiences a combination of flapwise and edgewise loads that are more in-keeping with the variable load combinations endured in operation. A real-time vision tracking system was developed to monitor the blade motion during the test. This vision data is integrated with real-time strain gauge data to provide the means for monitoring and controlling the test on the blade.

In parallel, in the project SUPERGEN Wind, STFC-RAL has developed a general, flexible, parametric, finite element model for wind turbine blade analysis. Within this model, the blade external geometry, internal structural shape, materials, loads, mesh, analysis type and post-processing operations can all be adjusted independently by the user. In particular, the application of industry standard materials and layups are compared with the use of more innovative materials. The model represents the basic operational conditions due to gravity, centrifugal and aerodynamic loads. The aerodynamic loading is applied as a fully distributed pressure field, resulting from constant user-specified wind speed, but accounting for wind shear and tower shadow effects, as well as a 2D aerofoil potential flow solution.

For this collaboration work, the innovative dual-axis NaREC loading system has been included within the STFC-RAL finite element model and analyses conducted to explore its performance characteristics. In the computational simulations, the blade model is loaded in a similar fashion to the dual-axis experiment; the analysis is time-based, non-linear and dynamic, featuring sinusoidal inertial load inputs as well as gravity. Experimental strain distributions measured during a dual-axis test are compared with the numerical predictions for the same load situation as well as for selected simple service load conditions produced computationally. Conclusions are drawn regarding the benefits of dual-axis resonant testing and its relevance for fatigue testing of large wind turbine blades. Furthermore, this work constitutes an element of validation for the finite element blade structural dynamics modelling tool.

Court RS, Ridley S, Jones H, Bonnet PA and Dutton AG, *Fatigue testing of wind turbine blades with computational verification*, 17th International Conference on Composite Materials (ICCM-17), Edinburgh, UK, 27th – 31st July 2009.

Online access: <http://www.supergen-wind.org.uk/publications.html>

ABSTRACT

A novel procedure for conducting wind turbine blade fatigue testing is presented. It features simultaneous loading in two orthogonal directions – flap and edge-wise – and uses the blade natural frequencies to force cyclic fatigue loads. This experimental scheme is modelled and studied with a finite element approach, using a full 3D blade model.

Djurovic S and Williamson S, *A coupled-circuit model for a DFIG operating under unbalanced conditions*, Proc. of the 2008 International Conference on Electrical Machines, Vilamoura, Portugal, September 2008. <http://www.supergen-wind.org.uk/publications.html>
ABSTRACT

The paper describes a time-stepped coupled-circuit model for a doubly-fed induction generator. The model, which is based on the summation of the harmonic winding inductances, is capable of representing both open- and short-circuit stator and rotor winding faults. The main purpose of this paper is to present evidence of the validity of this versatile and powerful technique and the advantages it offers when used for modeling and analysis of doubly-fed induction generator operation in unbalanced conditions.

Djurovic S and Williamson S, *Losses and pulsating torques in DFIGs with unbalanced stator and rotor excitation*, Proc. IEEE Int. Conf. on Sustainable Energy Technologies (ICSET2008), pp 328-333, Nov 2008. <http://www.supergen-wind.org.uk/publications.html>
ABSTRACT

ABSTRACT

This paper explores the operation of doubly fed induction generator (DFIG) under unbalanced supply conditions. Supply unbalance generally has a negative effect on induction machine operation, resulting in increased Joule loss and pulsating torques. The aim of this work is to quantify the effect that stator and/or rotor supply unbalance has on these aspects of DFIG performance.

Djurovic S, Williamson S and Renfrew A, (2009) *Dynamic model for Doubly-Fed Induction Generators with unbalanced excitation, both with and without winding faults*, IET Electric Power Applications, Vol. 3, No 3, pp 171-177.
<http://link.aip.org/link/?EPA/3/171/1>
ABSTRACT

ABSTRACT

A detailed analytical model designed for doubly-fed induction generator (DFIG) dynamic analysis is presented. The method employs a coupled-circuit approach and uses the principles of generalised harmonic analysis and complex conductor distribution to develop a systematic method for calculating a circuit's self inductance and mutual inductance for windings with any distribution of conductors. As such, it is capable of representing the effects that winding and excitation asymmetries have on machine performance. The accuracy of the model is verified in both the time and frequency domains against experimental results obtained from a specially constructed DFIG test rig, which can be configured to introduce a range of open-circuit and short-circuit faults. Model predictions are compared with experimental measurements for a balanced machine and for the case in which one stator phase suffers an open-circuit fault. The experimental and predicted data are shown to be in good agreement and demonstrate the effectiveness of the technique developed.

Djurovic S, Williamson S, Tavner PJ and Yang WX, *Condition monitoring artefacts for detecting winding faults in wind turbine DFIGs*, European Wind Energy Conference and Exhibition (EWEC2009), Marseille, France, March 2009.

Online access: <http://www.supergen-wind.org.uk/publications.html>

ABSTRACT

Monitoring the condition of doubly-fed induction generators (DFIG) is growing in importance for Wind Turbines. This study presents the results of a comparison of DFIG steady state stator line current and instantaneous power when used as a means for generator condition monitoring, based on an examination of their frequency spectrum. For the purpose of this work, a detailed analytical model that makes it possible to simulate DFIG operation under a range of supply and winding balanced/ unbalanced operating conditions, was developed. Additionally, a purpose-designed DFIG test rig was built to facilitate the experimental validation of model results. The faulty machine current and power spectra are compared using experimental and model results.

Tavner PJ, (2008) *Review of condition monitoring of rotating electrical machines*, IET Electric Power Applications, Vol. 2, No. 4, pp. 215-247.

Access online: <http://link.aip.org/link/?EPA/2/215/1>

ABSTRACT

Condition monitoring of rotating electrical machinery has received intense research interest for more than 30 years. However, electrical machinery has been considered reliable and the application of fast-acting digital electrical protection has rather reduced the attention operators pay to the equipment. The area based upon current literature and the author's experience is reviewed. There are three restrictions: only on-line techniques for rotating machines are dealt with; specific problems of variable speed drives are not dealt with, except in passing; conventional rather than emerging brushless, reluctance and permanent magnet machines of unusual topology are concentrated upon. The art of condition monitoring is minimalist, to take minimum measurements from a machine necessary to extract a diagnosis, so that a condition can be rapidly inferred, giving a clear indication of incipient failure modes. The current state of the art is reviewed in the following ways: survey developments in condition monitoring of machines, mechanically and electrically, over the last 30 years; put that work in context alongside the known failure mechanisms; review those developments which have proved successful and identify areas of research which require attention in the future to advance the subject.

Torres E, Djurovic S, Terzija V and Williamson S, *Application of Parameter Estimation Methods to the Assessment of DFIG's currents*, - Proc IEEE Int. Conf.

PowerTech, Bucharest, Romania, June/July 2009.

<http://www.supergen-wind.org.uk/publications.html>

ABSTRACT

Proliferation of nonlinear loads and development of renewable energy resources introduces new challenges in power quality monitoring due to the increased level of harmonic distortion of voltage and current signals. In this paper, the quality of harmonic distortion of currents recorded on a laboratory Double Fed Induction Generator drive is investigated. An efficient nonlinear estimation method is applied to evaluate the effects of interharmonic distortion in the estimation process. The results obtained are compared with those provided by the application of the Fast Fourier Technique (FFT).

Watson SJ and Xiang J, *Condition Monitoring of Wind Turbine Drive Trains*, UKERC

Sustainable Energy UK: Meeting the Science and Engineering Challenge, St Anne's College, Oxford, UK, 13th – 14th May 2008. <http://www.supergen-wind.org.uk/publications.html>

ABSTRACT

With a move to offshore wind farms, the need for effective and proactive condition monitoring of wind turbines becomes ever more acute, particularly with weather restricted maintenance. This paper presents a number of techniques for the prediction of potential wind turbine drive train failures including analysis of the active power produced by a wind turbine and the use of standard 10-minute SCADA data. High frequency analysis of the power signal is used to detect possible misalignment of the generator drive shaft. Bearing temperature is related to active power and trends analysed with respect to maintenance logs where generator bearing failures have been identified. Recommendations are made as to how such analysis techniques could be incorporated into an intelligent condition monitoring system.

Watson SJ, Xiang JP, Yang WX, Tavner PJ and Crabtree CJ, *Condition monitoring of a wind turbine doubly-fed induction generator*, EWEC2009, Marseille, France, March 2009. Online access: <http://www.supergen-wind.org.uk/publications.html>

ABSTRACT

This paper presents the results of work to analyse the power output of a wind turbine generator to detect eccentricities in the rotor/stator electrical field resulting from generator shaft misalignment. The power output has been analysed using a wavelet and the magnitude of the wavelet component at twice slip frequency tracked in time. This magnitude is shown to increase significantly during periods of field eccentricity as verified under controlled conditions in a lab test. The technique was then applied to two operational turbines and showed positive indications of shaft misalignment or bearing distress which were subsequently confirmed by maintenance.

With the move to offshore, the requirement for predictive and proactive maintenance of wind turbines has become ever more important. Misalignment of the generator drive shaft which may result in generator bearing failure is known to be one of the more frequent sources of failure in wind turbines and is a candidate for condition monitoring. Proximity sensors and vibration monitoring equipment can be used to detect bearing and shaft problems, but this type of equipment is expensive and may itself be prone to failure. In addition, installation of such equipment may require drilling and tapping of components within the drive train which could cause warranty or mechanical integrity problems. A simpler non-intrusive approach is to monitor the power output of the generator itself. This does not require any further equipment, merely, the averaging of data at a higher frequency than the SCADA standard of ten minutes. This paper presents the results of research using wavelets to analyse the power output of a doubly-fed induction generator sampled at 60Hz. In particular, the magnitude of the twice slip frequency component (2sf) is tracked in time as an indicator of eccentricity in the rotor/stator electromagnetic field which may indicate shaft misalignment and/or bearing wear. The technique was validated on a scale test rig under controlled conditions and its use was then demonstrated on two operational wind turbines of 1.5-2 MW in size. The results showed that shaft misalignment, which in one case resulted in bearing failure, were detectable up to two months in advance of the failure occurring. The results of the measurements were confirmed by subsequent maintenance action. The methodology described could easily be incorporated into a new or existing condition monitoring package for a wind turbine.

Watson SJ, Xiang BJ, Yang W, Tavner PJ, Crabtree CJ. (2010). *Condition Monitoring of the Power Output of Wind Turbine Generators using Wavelets*. IEEE Transactions on Energy Conversion, Vol. 25, No. 3, pp.715-721.

Online access: <http://dx.doi.org/10.1109/TEC.2010.2040083>

ABSTRACT

With an increasing number of wind turbines being erected offshore, there is a need for cost-effective, predictive and proactive maintenance. A large fraction of wind turbine downtime is due to bearing failures, particularly in the generator and gearbox. One way of assessing impending problems is to install vibration sensors in key positions on these subassemblies. Such equipment can be costly and requires sophisticated software for analysis of the data. An alternative approach which does not require extra sensors is investigated in this paper. This involves monitoring the power output of the wind turbine generator at frequencies up to ~30Hz and processing the data using a wavelet in order to extract the strength of particular frequency components, characteristic of faults. This has been done for doubly-fed induction generators (DFIGs), commonly used in modern wind turbines. The technique is first validated on a test rig under controlled fault conditions and then is applied to two operational wind turbine DFIGs where generator shaft misalignment was detected. For one of these turbines the technique detected a problem three months before a bearing failure was recorded.

Wilkinson MR and Tavner PJ, *Condition monitoring of wind turbine drive trains*, Proc. of the 17th International Conference on Electrical Machines (ICEM), Chania, Crete Island, Greece, 2006. Online access: <http://www.supergen-wind.org.uk/publications.html>

ABSTRACT

Condition-based maintenance for offshore wind turbines will improve reliability and increase the availability and hence the cash return for operators. Reliability studies and failure modes and effects analysis give an indication about which areas are most important. A test rig has been used to act as a model for a wind turbine and enable the development of a condition monitoring system concentrating on the drive train. This paper presents results from the test rig that shows the identification of harmonic content of the drive train, the detection of faults and the effect of different load conditions.

Wilkinson, MR, Spinato, F and Tavner, PJ *Condition Monitoring of Generators & Other Subassemblies in Wind Turbine Drive Trains*, 6th IEEE International Symposium on Diagnostics for Electric Machines, Power Electronics and Drives (SDEMPED 2007), Cracow, Poland, 6th – 8th Sept 2007. <http://www.supergen-wind.org.uk/publications.html>

ABSTRACT

Offshore wind turbines, incorporating electrical generators and converters, operate in locations where accessibility can lead to long mean times to repair. Condition-based maintenance is therefore essential if cost-effective availability targets are to be reached. As yet the condition monitoring techniques appropriate for offshore wind turbines have not been resolved. Reliability studies have shown that the majority of failure modes in wind turbines are concentrated in drive train subassemblies, including the electrical generator and converter, and are heavily affected by wind conditions. A 30 kW test rig has been constructed, with features similar to a wind turbine drive train, to enable the development of the signal processing techniques necessary for this variable speed, high torque variation application. The test rig includes a low speed shaft, high speed shaft, gearbox and an electrical generator and can be driven by simulated wind conditions. The test rig can also be used to inform the selection of appropriate monitoring instrumentation for offshore wind turbines. A series of condition monitoring approaches have been investigated on this test rig, using measured torque, speed, shaft displacement and gearbox vibration to detect faults. By the use of appropriate signal processing techniques, changes to load conditions, properties of the gearbox and coil faults can be detected.

Williamson S and Djurovic S, *Origins of Stator Current Spectra in DFIGs with Winding Faults and Excitation Asymmetries*, **Electric Machines and Drives Conference**, IEEE International (IEMDC '09), pp. 563-570, Miami, Florida USA, 3rd – 6th May 2009. Online access: <http://www.supergen-wind.org.uk/publications.html>

ABSTRACT

In this paper the authors derive simple expressions for the frequencies of the harmonic components in the steady state stator line current of a DFIG operating under various conditions of supply and/or winding unbalance. The underlying purpose of the work is to identify signature frequencies which may be used in condition monitoring instrumentation to both identify and discriminate between a range of likely faults that may arise in practice. The analytical expressions are verified first by comparison with the spectra calculated using an advanced time-stepped circuit model, and then by comparison with measurements made on an experimental test rig.

Yang, WX, Jiang JS, Tavner PJ and Crabtree CJ, *Monitoring wind turbine condition by the approach of empirical mode decomposition*, International Conference of Electrical Machines and Systems (ICEMS 2008), Wuhan, China 17th – 20th Oct 2008.

Online access: <http://www.supergen-wind.org.uk/publications.html>

ABSTRACT

An efficient condition monitoring system is indispensable to a large offshore wind turbine (WT) as it suffers higher reliability risk being exposed to extreme running environment and subject to constantly variable loadings, however difficult to access for fault repair. Today, the majority condition monitoring techniques for WT are borrowed from other industry fields where they achieve success. However, to date these techniques have not proved entirely satisfactory in wind industry. The reasons are various. But one of the main reasons is lack of a proper approach to the accurate analysis of WT signals, which are non-stationary in both time and frequency. The inaccurate analysis of WT signals results in frequent spurious alarms, which cause unnecessary shut down of machines and seriously disturb the normal production of wind farms. Aim at improving this situation, a new technique is developed in this work through analyzing the total power signals measured from the terminals of the WT generator by using the approach of Empirical Mode Decomposition (EMD). In comparison with those conventional Fourier transform-based techniques that are being popularly used today in wind industry, the EMD is more ideal for processing the non-stationary, nonlinear WT signals attribute to its intrinsic locally adaptive property. Additionally, the computational algorithm of the EMD is more efficient than that of previous wavelet analysis, which enables the EMD more suitable for use in online condition monitoring systems. The proposed approach has been experimentally validated on a deliberately designed WT test rig with a 3-phase induction generator. It has been proved that the proposed strategy is valid for detecting both drive train mechanical and generator electrical faults occurring in all types of WTs whether geared or direct-drive.

Yang WX, Tavner P J and Wilkinson MR, (2009) *Condition monitoring and fault diagnosis of a wind turbine synchronous generator drive train*, IET Renewable Power Generation, Vol. 3, No. 1, pp. 1-11. Online access: <http://link.aip.org/link/?RPG/3/1/1>

ABSTRACT

Some large grid connected wind turbines use a low-speed synchronous generator, directly coupled to the turbine, and a fully rated converter to transform power from the turbine to mains electricity. The condition monitoring and diagnosis of mechanical and electrical faults in such a machine are considered, bearing in mind that it has a slow variable speed and is subject to the stochastic, aerodynamic effects of the wind. The application of wavelet transforms is investigated in the light of the disadvantages of spectral analysis in processing signals subject to such stochastic effects. The technique can be used to monitor generator electrical and drive train mechanical faults. It is validated experimentally on a wind turbine condition monitoring test rig using a three-phase, permanent-magnet, slow-speed, synchronous generator, driven by a motor controlled by a model representing the aerodynamic forces from a wind turbine. The possibility of detecting mechanical and electrical faults in wind turbines by electrical signal and particularly power analysis is heralded.

Yang WX and Tavner PJ, *Wind turbine condition monitoring and fault diagnosis using wavelet transforms*, 4th PhD Seminar on Wind Energy in Europe, Magdeburg, Germany, 1st – 2nd Oct 2008. <http://www.supergen-wind.org.uk/publications.html>

ABSTRACT

Some large wind turbines use a synchronous generator directly-coupled to the turbine. This paper considers condition monitoring and diagnosis of mechanical and electrical faults in such a variable speed machine. The application of wavelet transforms is investigated because of the disadvantages of conventional spectral techniques in processing instantaneous turbine signals. In this paper a new condition monitoring technique is proposed which removes the negative influence of variable wind in machine condition monitoring. The diagnosis of rotor imbalance in the wind turbine will be done, heralding the detection of wind turbine electromechanical faults by power analysis.

Yang WX, Tavner PJ and Wilkinson M, *Condition monitoring and fault diagnosis of a wind turbine with a synchronous generator using wavelet transforms*, Proc. 4th IET Int. Conf. on Power Electrical Machines and Drives, York, April 2008.

Online access: <http://www.supergen-wind.org.uk/publications.html>

ABSTRACT

Some large wind turbines use a low speed synchronous generator, directly-coupled to the turbine, and a fully rated converter to transform power from the turbine to mains electricity. This paper considers the condition monitoring and diagnosis of mechanical and electrical faults in such a variable speed machine. The application of wavelet transforms is investigated because of the disadvantages of conventional spectral techniques in processing instantaneous information in turbine signals derived from the wind, which is variable and noisy. A new condition monitoring technique is proposed which removes the negative influence of variable wind in machine condition monitoring. The technique has a versatile function to detect mechanical and electrical faults in the wind turbine. Its effectiveness is validated by experiments on a wind turbine condition monitoring test rig using a permanent-magnet synchronous generator, which can be driven by aerodynamic forces from a drive motor controlled by an external model, representing wind and turbine rotor behaviour. Within the technique wavelet transforms are employed for noise cancellation and are extended to diagnose faults by taking advantage of their powerful capabilities in analysing non-stationary signals. The diagnosis of wind turbine rotor imbalance in the will be used as an illustrative example, heralding the possibility of detecting a wind turbine mechanical faults by power signal analysis.

Yang WX, Tavner PJ and Wilkinson M, *Wind turbine condition monitoring and fault diagnosis using both mechanical and electrical signatures*, Proceedings of the 2008 IEEE/ASME International Conference on Advanced Intelligent Mechatronics, Xi'an, China, 2-5 July 2008. Online access: <http://www.supergen-wind.org.uk/publications.html>

ABSTRACT

Some large wind turbines use a synchronous generator, directly-coupled to the turbine, and a fully rated converter to transform power from the turbine to the mains. This paper considers condition monitoring and diagnosis of mechanical and electrical faults in such a variable speed machine. A new condition monitoring technique is proposed in this paper, which removes the negative influence of variable wind in machine condition monitoring. This technique has a versatile function, able to detect both the mechanical and electrical faults in the wind turbine. Its effectiveness is validated by the experiments on a wind turbine condition monitoring test rig. Furthermore, a potential approach for diagnosing wind turbine drive-train mechanical faults using wind turbine generator electrical signals is introduced. The diagnosis of rotor imbalance in the wind turbine will be used as an illustrative example, heralding the detection of wind turbine electromechanical faults by power analysis. The paper offers a simpler and cheaper condition monitoring and fault diagnosis system for wind turbines.

Yang WX, Tavner PJ, Crabtree CJ and Wilkinson M, *Research on a simple, cheap but globally effective condition monitoring technique for wind turbines*, Proceedings of the 2008 International Conference on Electrical Machines, Vilamoura, Portugal, 2008.

Online access: <http://www.supergen-wind.org.uk/publications.html>

ABSTRACT

Vibration measurement and lubrication oil analysis are used in wind turbines (WT) as condition monitoring systems (CMS). However, they do not provide a complete solution to the WT CMS problem. The former measurement is sophisticated with high hardware costs, suffering from spurious alarms; the latter monitors the wear and fatigue of gears and bearings, but cannot detect electrical abnormalities occurring in the WT generator and electrical system. So, a simpler, cheaper but moreover globally comprehensive WT CMS is still needed, especially if the WTs are to go offshore, where they are confronted with higher risks and difficulties of access. To meet this requirement, a new WT condition monitoring technique has been researched in this paper. As the WT operates over a widely varying power range, dependant on the stochastic variations of the wind, the monitoring signals are usually non-stationary. In view of this, a wavelet-based adaptive filter is designed to extract the power energy at prescribed, fault-related frequencies which vary with time. The energy information obtained is then used as an indicator of WT condition. The central frequency of the filter is adaptive to the average rotational speed of the generator, and the filter bandwidth depends upon the fluctuation of wind speed. By using this filter, fault features can be extracted whether the WT runs at fixed or variable speed. The proposed technique has been experimentally validated on a WT Test Rig using both synchronous and induction generators as exemplars. Experiments prove that the proposed technique is efficient in assessing the WT condition for both mechanical and electrical abnormalities.

Yang WX, Tavner PJ and Crabtree CJ, *An intelligent approach to the condition monitoring of large scale wind turbines*, EWEC 2009, Marseilles, France, March 2009.

Online access: <http://www.supergen-wind.org.uk/publications.html>

ABSTRACT

In view of the limitations of the condition monitoring (CM) techniques nowadays available for wind turbines (WTs), a fully intelligent condition monitoring technique has been developed in this paper using Empirical Mode Decomposition (EMD). The EMD method is characterized by its powerful capability in processing non-stationary and nonlinear signals and by being an efficient sifting algorithm. The effectiveness and the merits of the proposed technique in wind turbine condition monitoring have been experimentally validated on a Wind Turbine Condition Monitoring Test Rig.

Yang, WX, Tavner, PJ, Crabtree, CJ and Wilkinson M (2010). *Cost-effective condition monitoring for wind turbines*, IEEE Transactions on Industrial Electronics. Vol. 57, No. 1, pp. 263-271, Online access: <http://dx.doi.org/10.1109/TIE.2009.2032202>

ABSTRACT

Cost-effective wind turbine (WT) condition monitoring assumes more importance as turbine sizes increase and they are placed in more remote locations, for example, offshore. Conventional condition monitoring techniques, such as vibration, lubrication oil, and generator current signal analysis, require the deployment of a variety of sensors and computationally intensive analysis techniques. This paper describes a WT condition monitoring technique that uses the generator output power and rotational speed to derive a fault detection signal. The detection algorithm uses a continuous-wavelet-transform-based adaptive filter to track the energy in the prescribed time-varying fault-related frequency bands in the power signal. The central frequency of the filter is controlled by the generator speed, and the filter bandwidth is adapted to the speed fluctuation. Using this technique, fault features can be extracted, with low calculation times, from direct or indirect-drive fixed- or variable-speed WTs. The proposed technique has been validated experimentally on a WT drive train test rig. A synchronous or induction generator was successively installed on the test rig, and both mechanical and electrical fault-like perturbations were successfully detected when applied to the test rig.

Condition monitoring system

The research in condition monitoring system has resulted in three papers describing two quite different approaches which have shown predictive value in terms of failures particularly with regard to the wind turbine drive train which is the largest source of wind turbine downtime. The first two of these relate to an analysis of SCADA data and apply a) a physics of failure approach and b) an ARX model to predicting failure. In the first of these two papers, the analysis technique is applied to the wind turbine gearbox. The second paper looks at generator bearings. In the case of the third paper, higher frequency measurements of the power output of a turbine are used to predict possible generator bearing problems.

Crabtree CJ and Tavner PJ, *Condition Monitoring of Wind Turbines*, 5th PhD Seminar on Wind Energy in Europe, Durham, 30th Sep – 1st Oct 2009.

Online access: <http://www.supergen-wind.org.uk/publications.html>

ABSTRACT

Condition monitoring (CM) of wind turbines (WT) is assuming greater importance as the installed capacity of wind turbines increases. This paper briefly describes a test rig for the development of CM techniques for WTs. The test rig includes features of a WT including its variable speed and torque nature, a simple gearbox, induction generator and grid connection. 'Fault-like perturbations' are applied to the rig and signals recorded and analysed. This paper gives an example of fault detection in the three phase power signal by tracking fault frequencies using a wavelet energy tracking method.

Crabtree CJ, Feng Y, and Tavner PJ, *Detecting incipient wind turbine gearbox failure: a signal analysis method for on-line condition monitoring*, Proceedings EWECE 2010, Scientific Track, Oral Presentation, Warsaw, 20th – 23th Apr 2010.

Online access: <http://www.supergen-wind.org.uk/publications.html>

ABSTRACT

Condition monitoring of wind turbines is gaining importance as turbines become larger and move to more inaccessible locations, such as offshore. Condition monitoring based on methods conventionally used in the power generation industry have been demonstrated to work successfully on large wind turbines when attention is paid to data collection. In view of the large number of wind turbines deployed this paper proposes a methodology for wind turbine condition monitoring that compares conventional condition monitoring signals with operational signals, such as load or energy, which could be applied automatically. A multi-parameter approach, based on comparison of independent signals, should increase confidence in fault signal interpretation and alarms generated, potentially reducing the risk of false alarms.

Crabtree CJ, Djurovic S, Tavner PJ, and Smith AC, *Condition monitoring of a wind turbine DFIG by current or power analysis*. PEMD2010, Brighton, April 2010.

Online access: <http://www.supergen-wind.org.uk/publications.html>

ABSTRACT

As wind energy assumes greater importance in remote and offshore locations, effective and reliable condition monitoring techniques are required. This paper proposes a method analysing electrical signals from the stator terminals of the wound rotor induction generators commonly used in wind turbines. Analytical equations have been derived for the frequency content of line current and total instantaneous power for healthy and faulty wound rotor induction generators and these have been used to analyse signals from test rigs in the steady state. Analysis at constant speed yields a set of equation constants which describe the frequencies of most interest as observed from the test rig environments. Having discovered a consistent group of fault frequencies the data is then demonstrated at variable speed to show the variability of those fault frequencies with speed. It is concluded that tracking these speed dependent fault frequencies will be an effective way to monitor the health of a wound rotor induction generator in a wind turbine.

Garlick WG, Dixon R and Watson SJ, *A Model-based Approach to Wind Turbine Condition Monitoring using SCADA Data*, ICSE 2009, Coventry, September 2009.

Online access: <http://www.supergen-wind.org.uk/publications.html>

ABSTRACT

Modern wind turbines are complex aerodynamic, mechanical and electrical machines incorporating sophisticated control systems. Their design continues to increase in size and they are increasingly being positioned offshore where the environment is hostile and where there are limited windows of opportunity for repair and maintenance activities. Condition monitoring is essential offshore if Wind Turbines (WTs) are to achieve the high reliability necessary for sustained operation. Contemporary WT monitoring systems already provide vast amounts of data, the essential basis of condition monitoring, much of which is ignored until a fault or breakdown occurs. This paper presents a model-based approach to condition monitoring of WT bearings. The backbone of the approach is the use of a least squares algorithm for estimating the parameters of a discrete time transfer function (TF) model relating WT generator temperature to bearing temperature. The model is first fitted to data where it is known no problems exist. It is then used in predictive mode and the estimates of the bearing temperature are compared with the real measurements. The authors propose that significant discrepancies between the two are indicative of a developing problem with the bearings. The promising experimental results achieved so far indicate that the approach is viable.

Gray CS and Watson S, (2009) *Physics of Failure Approach to Wind Turbine Condition Based Maintenance*, Wind Energy, Vol. 13, Issue 5. pp 395-405.

<http://dx.doi.org/10.1002/we.360>.

ABSTRACT

Wind turbine condition monitoring systems provide an early indication of component damage, allowing the operator to plan system repair prior to complete failure. However, the resulting cost savings are limited because of the relatively low number of failures that may be detected and the high cost of installing the required measurement equipment. A new approach is proposed for continuous, online calculation of damage accumulation using standard turbine performance parameters and Physics of Failure methodology. The wind turbine system is assessed in order to identify the root cause of critical failure modes and theoretical damage models are developed to describe the relationship between the turbine operating environment, applied loads and the rate at which damage accumulates. Accurate estimates may then be made in real time concerning the probability of failure for specific failure modes and components. The methodology is illustrated for a specific failure mode using a case study of a large wind farm where a significant number of gearbox failures occurred within a short space of time. Such an approach may be implemented at relatively low cost and offers potential for significant improvements in overall wind turbine maintenance strategy.

Xiang J and Watson SJ, *Practical Condition Monitoring Techniques for Offshore Wind Turbines*, European Wind Energy Conference (EWEC2008), Brussels, Belgium, 31st March – 3rd

April 2008. <http://www.supergen-wind.org.uk/publications.html>

ABSTRACT

Condition monitoring of wind turbines has become important particularly for offshore wind farms. However modern offshore wind turbines are operated at variable speed and the offshore environment is technically challenging. Therefore online condition monitoring and relatively complex data processing methods are crucially needed. This paper presents some new methodologies and results of work to analyze both ten-minute standard SCADA data and medium frequency sampled power data for the purposes of detecting potential faults, particularly in the wind turbine drive train. The SCADA data have been de-trended or daily screened over time. Power data sampled at 30Hz /32Hz have been analyzed using Morlet wavelet transform, Fast Fourier Transform (FFT) and root mean square (RMS). Some examples, including the detection of the potential generator shaft misalignment and generator bearing fault from the slip frequency components in a power signal, are discussed.

4.4 Theme Y: Structural loads and materials

Theme leader: Loughborough University

Partners: Loughborough University
 Rutherford Appleton Laboratory
 Manchester University
 Surrey University
 University of Strathclyde

4.4.1 Introduction

This theme looks towards the reliable, safe, and effective operation of current 1.5-5.0 MW wind turbines and future 5+ MW turbines. To determine how machine loads can best be controlled at this scale and to assess whether there exist design limits which might ultimately limit machine size, the Theme looks at wind flow and wake effects, the use of novel materials, advanced structural models and control strategies so that future large scale wind turbines can be designed as materially optimised, load tolerant, reliable, long-lifetime, cost-effective structures.

4.4.2 Research outputs

The research outputs are grouped by four research topics in this theme.

Wake effects on blade loading

One deliverable report and one conference paper highlight research outputs in the wake effects on blade loading.

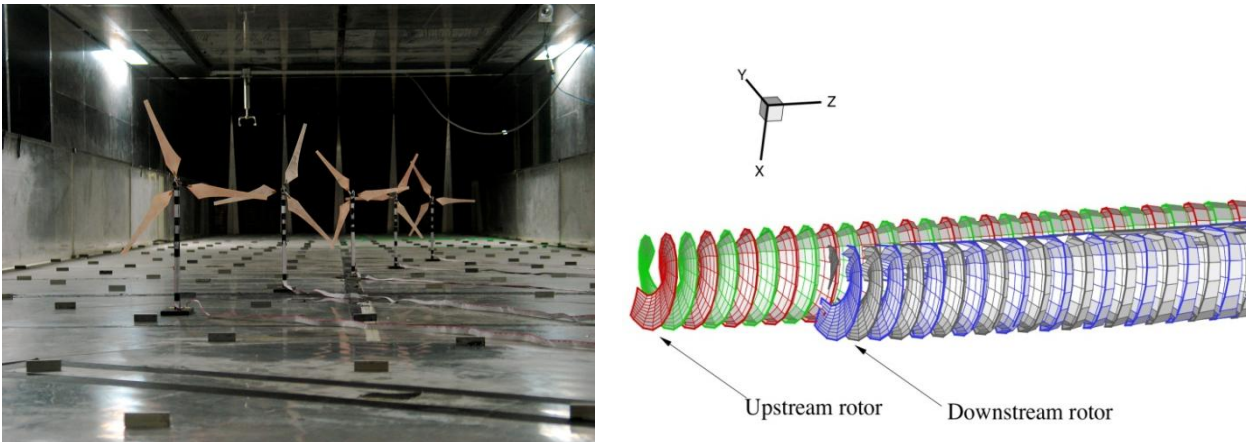


Figure 3 Wind farm wake measurements and Twin bladed rotor wake

Graham JMR, Bampalas N, and Whelan J (2009) *DY.1.1 Improved Model for large wake loads*, SUPERGEN Wind Technologies.

Online access: <http://www.supergen-wind.org.uk/members/members.html>

ABSTRACT

Nine items has been worked in this topic, and is reported in this deliverable. Items 1-5 concerned with wake model, rotor interaction and rotor loading. Work items 6 to 9 concerned with wind tunnel testing of a model rotor subject to impinging wakes in a simulated atmospheric boundary layer (ABL).

1. Development of a free vortex wake model based on vortex ring (or dipole) panels.
2. Wake interaction with ground plane and ABL shear.
3. Interaction of two rotors, one downstream of the other.
4. Rotor Interaction with Incident Turbulence and use of an Indicial Method.
5. Simulation of Turbulent Inflow and application to rotor loading.
6. Design, construction and commissioning of an instrumented model rotor.
7. Measurements of in- plane and out- of- plane forces carried out in a simulated ABL.
8. Construction and commissioning of an upstream wake generating rotor.
9. Measurements of forces on the downstream rotor subject to an incident wake.

Bampalas N and Graham JMR, *Aerodynamic Rotor Model for Unsteady Flow and Wake Impact*, Wind Energy Colloquium, University of Oldenburg, Germany, 30th June - 2nd July 2008. Online access: <http://www.supergen-wind.org.uk/publications.html>

ABSTRACT

A code has been developed based on free wake vortex lattice theory. The method includes viscous corrections to the blade section lift and drag, to model the aerodynamic response of a horizontal axis wind turbine rotor in unsteady flow. An indicial method is used to carry out sufficiently long computations to build up converged statistics of the response characteristics of the rotor in a turbulent flow. This model is being run currently in an incident flow modelling homogeneous turbulence. Following this, the model will be used to establish the statistics of unsteady forces induced by interaction of the rotor with incident wakes of upwind turbines in array configurations.

Novel materials

Novel material for blades has been modelled and tested by the Consortium. Results can be viewed in the following two reports and two papers.

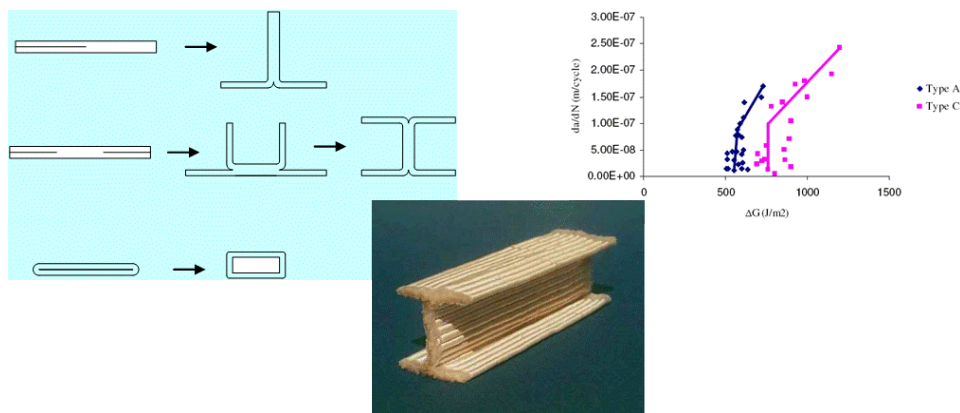


Figure 4 Blade material model and test

Hogg PJ and Jamshidi M (2009), *DY.1.2 Report on novel materials for blades, SUPERGEN Wind Technologies*. <http://www.supergen-wind.org.uk/members/members.html>
INTRODUCTION

This report examines the materials current in use for wind turbine blades and identifies future developments, both in terms of new materials and the direction that the industry is taking in terms of materials process combinations.

The predominant materials used for wind turbine construction are E-glass fibre composites with either epoxy resins or vinyl ester/polyesters as the matrix material. There are alternative materials that are found in specific designs with high performance glass fibre being used in small quantities and an increasing tenancy for the use of carbon fibres

The actual mix of materials within a blade can be relatively complex with the structural elements (spars and Skins) sometimes including laminate wood, and inserts of carbon pultrusions and pre-moulded spars. The interstices between the skins and the spars may be open or filled with lightweight porous materials such as foams, honeycomb and balsa.

There is a growing use of coatings on the blades themselves to provide environmental protection against wind rain and erosion due to sand and other particulates. At this time additional function items such as lightning protection is not incorporated as an integral part of the blade structure, but rather as an additional item and this is also the case for condition monitoring sensors, although all of these items could be embedded in the main composite structure of the blade.

Hogg PJ and Jamshidi M (2009), *DY.1.4 Report on tower materials, SUPERGEN Wind Technologies*. Online access: <http://www.supergen-wind.org.uk/members/members.html>
INTRODUCTION

This report examines the materials current in use for wind turbine towers and identifies future developments, both in terms of new materials and the direction that the industry is taking in terms of materials process combinations.

The predominant materials used for wind turbine towers are steel and concrete. Due to various reasons that will be explained in following sections alternative materials has been introduced in small scales. With rotor diameters and turbine weight increasing, the demands on the towers are equally increasing. As the towers grow taller, the overturning moment increases at the base of the tower. Therefore application of new materials in some parts needed. There is a growing use of composite foundation especially for offshore wind turbines which is a combination of concrete and steel. As the depth of water in offshore increasing floating wind turbine concept has been introduced.

Dutton AG, Bonnet PA, Hogg P and Lleong YL, (2009) *Novel materials and modelling for large wind turbine blades*, Journal of Power and Energy, Vol. 224, No 2, pp 203-210.

Online access: <http://dx.doi.org/10.1243/09576509JPE858>

ABSTRACT

Commercial wind turbines have developed incrementally in size over the last thirty years so that the largest wind turbine up to the end of 2005 had a rated output of 5 MW, rotor diameter 124 m and individual blade weight of 18 tonnes. The question therefore arises as to what the ultimate limits on turbine size might be.

Potential design limiting factors in wind turbine design include:

- static and fatigue strength,
- overall rotor mass (has implications for tower head mass, structure, and foundations),
- blade stiffness (required to ensure clearance between the blade tip and the wind turbine tower),
- blade and tower transportability.

The paper presents work carried out within the EPSRC SUPERGEN Wind Consortium on the potential use of novel materials in wind turbine blades and the resulting consequences for blade strength and integrity. A generalised, parametric finite element wind turbine blade model has been developed and applied to a "baseline" blade design.

Results are presented on static and fatigue strength for new fibre materials and how they can be incorporated into the blade model to demonstrate the likely impact on blade stiffness, strength, and weight. Possible future developments in blade structural design will be discussed in the context of other potential material innovations and "smart" control concepts.

Hogg PJ, Ren G, Peace S and Marsh, P, *The advantages of composite materials in new design concepts for wind turbines*, Conference on Composites Processing 2006,

Haydock, 27th April 2006. Online access: <http://www.supergen-wind.org.uk/publications.html>

ABSTRACT

The continued need for an increase in the percentage of energy generation that can be attributed to renewable sources will drive an expansion of wind power while a need to reduce energy costs will simultaneously drive innovation in wind turbine design.

The introduction of new materials including improved glass fibre and increasing quantities of carbon fibres will extend the performance range of large horizontal axis turbines, but due to weight and transport restrictions this is not an unlimited process. It is likely that horizontal axis wind turbines are very close to the limits of the growth, despite now reaching unprecedented levels of operating efficiency.

Vertical axis machines offer a route to continuing to increase turbine output levels whilst retaining some control on turbine size and installation and manufacturing costs. The very significant problem of self-weight fatigue is dramatically reduced, along with issues such as susceptibility to wind direction and the ability to operate over a large range of wind speeds.

If low cost manufacturing processes can be harnessed effectively, then it should be possible to develop a new generation of wind turbines in the 10MW range whilst maintaining or even reducing the existing price band of wind energy.

The viability of vertical axis wind turbines will depend on the exact manufacturing strategy adopted and a number of possible processing/assembly options must be considered. It is clear that some form of composite structure coupled with a low cost process route, at least in part involving pultrusion is an attractive prospect for these machines.

Structural blade model

STFC-RAL has developed a parametric structural blade model written in Python script which acts as a front end to one or more Abaqus finite element analyses, allowing quick changes to blade profile, geometry, loading, and mesh parameters. The model is capable of carrying out sweeps on all input parameters as the basis of optimisation studies.

The blade model has been developed initially as a quasi-static model with ability to predict potential blade failure mode. Application of the model to the assessment of innovative materials in blade design is only now being completed due to delays in delivery of experimental data from other partners.

In the meantime, the model has been applied to the interpretation of blade test measurements (see deliverable X1.1) and to preliminary studies of smart blade features (see case study 3 in draft paper below).

The blade model is further capable of use for supporting condition monitoring application through the appropriate location of sensors, the interpretation of measurements, and the assessment of damage criticality.

Additional work is now underway to develop a fully dynamic model suitable for fully supporting work in aeroelastics and smart structures.

Outputs of this topic comprises a paper accepted for publication in Journal of Power & Energy, which briefly describes the model and its application to materials data; a second paper to be submitted shortly to Wind Energy containing a more comprehensive description of the model; and a third one including comparison of model outputs on thermoelastic stress measurements from a laboratory blade test.

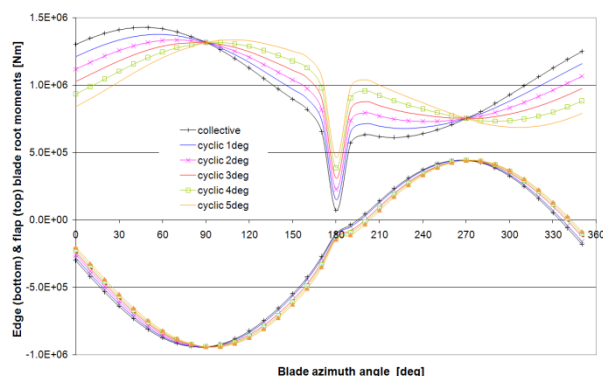
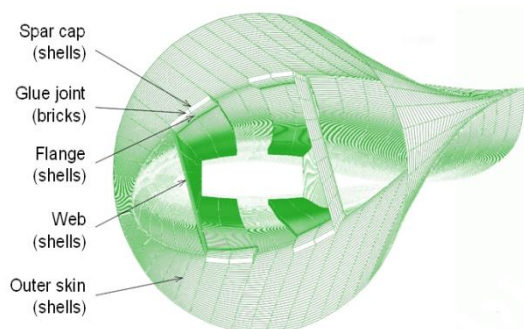


Figure 5 Blade model

Bonnet PA and Dutton AG, *Structural analysis tool for wind turbine blades*, under preparation for Wind Energy.

ABSTRACT

This paper presents a modelling tool for the study of wind turbine blades. The model is based on a commercial 3D finite element analysis package, made fully parametric, integrated and automated via a script pre-processor module. Gravity and centrifugal loads, and the effects of large deflections, are taken into account and realistically modelled in non-linear static analyses. The aerodynamic loading is also fully integrated into the parametric model, using a blade element momentum solution augmented with a 2D aerofoil analysis code for providing the aerofoil performance data. The method results in the automatic application of the aerodynamic load as a fully distributed pressure field on the blade surface. Three simple case studies are presented to show the potential usefulness of the modelling method. It is shown that the model responds well and is suitable for the study of quasi-static non-linear structural analysis of blades; future development will address dynamic and failure phenomena leading towards a multi-disciplinary dynamic analysis tool for wind turbine blades, capable of interacting with complete turbine models.

Bonnet PA and Dutton AG, *Finite element modelling of blade thermoelastic stress analysis results*, European Wind Energy Conference (EWEC2008), Brussels, 31st March – 3rd April 2008. Online access: <http://www.supergen-wind.org.uk/publications.html>

ABSTRACT

Thermoelastic stress analysis (TSA) is a non-destructive method that is used to assess structural stress. It is based on the ability to measure stress induced thermal emissions during cyclic loading with an infrared camera. It has potential applications for the monitoring of wind turbine blades certification tests. In this work, conducted as part of the UK SUPERGEN Wind Consortium, finite element (FE) analyses are conducted to evaluate the potential correlation with TSA outputs. Such correlation of FE and TSA for composite blade structures is key for the interpretation of TSA results and thus for the application of thermoelasticity to wind turbine blades. A flexible parametric structural model for wind turbine blades is presented, based on a Python script and the ABAQUS solver. Typical wind turbine blade geometry, which can be tailored by the user, enables the generation of a regular mapped mesh. The application of industry standard materials and layups is also enabled, as well as various loading types. It is then shown through a particular case study using a 4.5m long blade that the main characteristic stresses of the loaded structure are reasonably well represented by both the FE and TSA techniques and that some manufacturing defects can be detected at an early stage by TSA measurements. This is encouraging and suggests that the use of TSA should be pursued by the wind energy sector.

Dutton AG, Bonnet PA, Hogg P and Lleong YL, (2009) *Novel materials and modelling for large wind turbine blades*, accepted for publication in Journal of Power and Energy.

ABSTRACT

Commercial wind turbines have developed incrementally in size over the last thirty years so that the largest wind turbine up to the end of 2005 had a rated output of 5 MW, rotor diameter 124 m and individual blade weight of 18 tonnes. The question therefore arises as to what the ultimate limits on turbine size might be.

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The paper presents work carried out within the EPSRC SUPERGEN Wind Consortium on the potential use of novel materials in wind turbine blades and the resulting consequences for blade strength and integrity. A generalised, parametric finite element wind turbine blade model has been developed and applied to a "baseline" blade design.

Results are presented on static and fatigue strength for new fibre materials and how they can be incorporated into the blade model to demonstrate the likely impact on blade stiffness, strength, and weight. Possible future developments in blade structural design will be discussed in the context of other potential material innovations and "smart" control concepts.

Active load reduction

Research in this topic has been made progress in load reduction for turbine blades and tower through control system. A tower feedback loop in the wind turbine controller was included to alleviate tower load, which adds an incremental adjustment to the controller collective pitch demand in response to a measurement of tower head velocity or, equivalently, acceleration. A novel approach, Individual Blade Control (IBC) is investigated, which can control unbalanced rotor loads and tower head loads on a wind turbine.

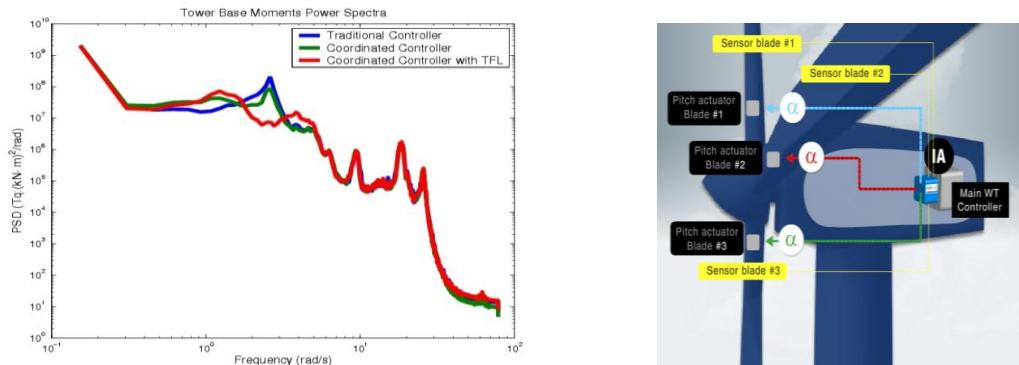


Figure 6 Load reduction with coordinated controller

Chatzopoulos A, Domingues S and Leithead WE (2009), *DY.3.1 Generic models of tower/blades dynamics*, SUPERGEN Wind Technologies.

Online access: <http://www.supergen-wind.org.uk/members/members.html>

ABSTRACT

The fundamental approach to tower load alleviation is by inclusion of a tower feedback loop in the wind turbine controller. This loop adds an incremental adjustment to the controller collective pitch demand in response to a measurement of tower head velocity or, equivalently, acceleration. The dynamic interaction of the tower, rotor and drive-train must be taken into account to make this approach effective. The achievable lifetime equivalent tower fatigue loads reduction is typically about 5%-9% depending on the particular characteristics of the wind turbine. When applied to the SUPERGEN 2MW and 5MW exemplar wind turbines, the reduction is 8% and 4.2%, respectively. The latter is unusually low but is due to the second tower mode rather than the first tower mode being the most important structural dynamics contribution to the tower fatigue. The reason for this is that the second tower mode coincides with 6P. The design of the tower feedback loop for the SUPERGEN exemplar wind turbines is discussed in detail in *Controller design and evaluation for the 5MW SUPERGEN exemplar wind turbine* and *Controller design and evaluation for the 2MW SUPERGEN exemplar wind turbine*. The design of the central controllers is also described in full.

An alternative approach to tower load alleviation has been developed. The central controller regulates both the wind turbine rotor speed and torque/generated power. In above rated wind speed conditions, the former is controlled by adjusting the pitch angle of the blades. The latter is controlled through the generator. Generally, these two feedback loops are designed separately. Instead, taking into account the dynamic interaction between the feedback loops, a coordinated approach is adopted whereby the need to minimise tower fatigue is taken into account when designing the rotor speed and torque feedback loops. The implementation issues related to this coordinated controller are also addressed; in particular, the strongly nonlinear aerodynamics, the switching between control modes and the actuator constraints. In essence, it is a structured multivariable controller. Without compromising any of the standard performance objectives, the reduction in the lifetime equivalent tower fatigue loads achieved by the coordinated controller is typically 10%-12%. With the addition of a tower feedback loop the tower fatigue life is further reduced to roughly, 15%-18%. The design and results of coordinated control is reported in the paper *Coordinated control design for wind turbine control systems*.

Neilson V and Leithead WE, (2009) *DY.3.2 Related strategies for maximum load reduction*, SUPERGEN Wind Technology Deliverable.

<http://www.supergen-wind.org.uk/members/members.html>

ABSTRACT

A novel approach to the control of unbalanced rotor loads and tower head loads on a wind turbine, Individual Blade Control (IBC), is investigated. The basic concept of the IBC is to control the pitch angle of each blade locally without interfering with the centralised collective pitch control. This requires a control structure consisting of an outer loop aimed at speed regulation and inner loops aimed at blade fatigue load reduction.

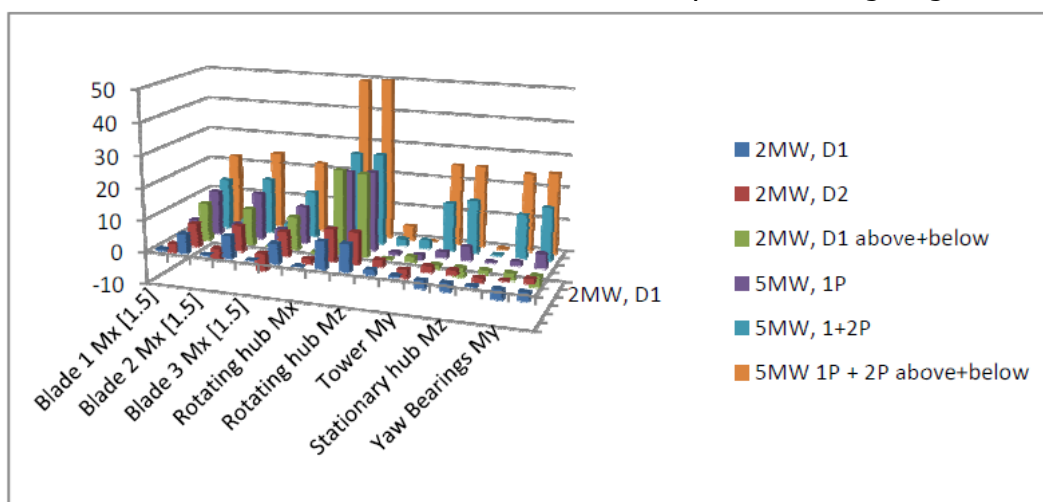
To analyse the operation of the inner outer control loops and their mutual interaction, the inner loop dynamics of the single blade are separated into two components, the dynamics in an inertial frame and the fictitious forces equivalent to the dynamics of the rest of the turbine. Rigid body dynamics analysis is used throughout the derivations of the equations of motion.

Only the first dynamic blade mode is included since the higher modes have little impact on the controller design and performance. The dynamic analysis is discussed in full in *Individual Blade Control – Blade model, Validation and Control Design* and reported in *Alleviation of Unbalanced Rotor Loads by Single Blade Controllers*

A baseline turbine model is used for validating the single blade model. This baseline model consists of a rotor model based on a single-blade concept, a gear box model and a tower model. To validate the single blade model, a rotor Lagrangian is derived with the same notations and reference frames as used for the fictitious forces and is compared to that of the baseline model. Results have shown that they are comparable.

Several issues have been addressed for the baseline turbine model. These include the derivation of a numerical solution to the effective wind speed using the same Bladed point wind input, the correct model of the spectral peaks, introduction of a tower shape factor so that the tower deflections can be calculated appropriately and a lumped parameter blade model that more accurately represents the turbine blade as it gets bigger and more flexible.

Design approaches for the IBC are discussed in the paper *A Novel Approach to Structural Load Control using Intelligent Actuators*. IBC has been applied to two exemplar turbines, a 2MW machine and a 5MW machine. The results are summarised by the following diagram.



A reduction of 11.76% in the blade’s lifetime equivalent fatigue loads and 26.04% in the rotor are observed for the 2MW turbine; whereas for the 5MW turbine, a significant fatigue load reduction of 22.3% on the blades and 49.25% on the rotor are achieved. Furthermore, the reduction in the mean and extreme overturning moment is substantial; for example, for the 5MW machine, at 20m/s average wind speed, the mean load imbalance is reduced from 4.73MNm to 0.23MNm and the extreme from 16.55MNm to 7.29MNm. On all aspects of the central controller operation, the impact on performance was neutral.

Dominguez S and Leithead WE, *Control design toolbox for large-scale PRVS wind turbines*, Proceedings of the 2007 EWEA European Wind Energy Conference (EWEC2007), Milan. 7th – 10th May 2007. Online access: <http://www.supergen-wind.org.uk/publications.html>
ABSTRACT

The trend towards large multi-MW wind turbines has given new impetus to the development of wind turbine controllers. Additional objectives are being placed on the controller making the specification of the control system more complex. A new toolbox, which assists with most of the control design cycle, has been developed. Its purpose is to assist and guide the control system designer through the design cycle, thereby enabling faster design. With the choice of control strategy unrestricted, the toolbox is sufficiently flexible to support the design process for the aforementioned more complex specifications.

Leithead WE and Dominguez S, *Coordinated control design for wind turbine control systems*, EWEC2006, Athens, Greece, 27th February – 2nd March 2006. Online access: <http://www.supergen-wind.org.uk/publications.html>
ABSTRACT

Increasingly, variable speed regulated wind turbine control systems are being required to alleviate structural loads. In standard approaches to alleviating tower loads, coupling of the generator speed and tower speed control causes reduced effectiveness of not only the tower speed loop itself but also the generator speed loop. Using improved representation of the wind turbine dynamics and catering specifically for the interaction of the two loops, a new configuration of control system, for a variable speed pitch regulated wind turbine is derived that, by most performance measurements, out-performs standard controllers.

Leithead WE and Dominguez S, (2007) *Active regulation of multi-MW wind turbines: an overview*, Power System Technology, Vol. 31, No. 20, pp. 24-34.
<http://www.dwjs.com.cn/EN/article/downloadArticleFile.do?attachType=PDF&id=21558>

ABSTRACT

With the recent trend towards large multi-MW wind turbines, the role of the control system has become increasingly important and its design increasingly demanding. Furthermore, the realisation that not only the performance of the machine but also the structural loads depend on the controller, has given research into the control of wind turbines a new impetus. The extension of the role of the controller to alleviate structural loads has motivated the exploration of novel control strategies, which seek to maximise load alleviation by exploiting the blade pitch system. An overview to raise awareness of the possibilities and potential of control for multi-MW wind turbines is presented. The place within the wind energy technology of the control system and its role as an integrating technology together with the perspective of the developers are discussed.

Leithead WE and Dominguez D, *The role of the control system for multi-MW wind turbines*, UKERC Sustainable Energy UK: Meeting the Science and Engineering Challenge, St Anne's College, Oxford, UK, 13th – 14th May 2008.

Online access: <http://www.supergen-wind.org.uk/publications.html>

ABSTRACT

Wind turbine technology has undergone a rapid development over the last three decades with the size of machines increasing markedly. Today, commercial wind turbines with a rating up to 5MW are available. After exploring many different concepts (one-bladed machines, two-bladed machines, vertical axis machines, constant speed, etc.), the industry standard has now settled on what is known as the Danish Concept, a three bladed up-wind horizontal-axis machine. The generator may be connected directly to the electricity grid by an asynchronous generator or indirectly by a power converter. In the former, the rotational speed of the rotor is constant, being fixed by the frequency of the grid, and the machine is a constant speed wind turbine. In the latter, the rotational speed of the rotor can vary and the machine is a variable speed wind turbine. The wind turbines considered in this paper are large multi-MW variable speed wind turbines.

To ensure that the wind turbine is operated in an appropriate manner, its aerodynamic torque and rotor speed must be regulated to maintain the machine at the operating point appropriate to the prevailing wind speed. The associated control system acts by varying the generator reaction torque and/or varying the angle of pitch of the blades about their longitudinal axis. The blades may be pitched in unison with all blades being set to the same angle, collective pitch, or pitched separately, individual pitch.

With the trend towards large multi-MW wind turbines, the role of the control system has become increasingly important and its design increasingly demanding. Control is an integrating technology that depends on most aspects of wind turbine technology and is relevant to several aspects of the turbine design. In addition, it affects the life-time performance and reliability of the machine. Improved control more suited to multi-MW wind turbines could benefit, albeit differently, both the manufacturers and developers. Furthermore, the realisation that not only the performance of the machine but also the structural loads depend on the controller, has given research into the control of wind turbines a new impetus. The extension of the role of the controller to alleviate structural loads has motivated the exploration of novel control strategies, which seek to maximise load alleviation by exploiting the blade pitch system.

A broad overview of the possibilities and potential of control for multi-MW wind turbines is presented. The place within the wind energy technology of the control system and its role as an integrating technology together with the perspective of the developers are discussed.

Leithead WE, Neilson V and Dominguez S, *Alleviation of unbalanced rotor loads by single blade controllers*, EWEC2009, Marseilles, France, March 2009.

Online access: <http://www.supergen-wind.org.uk/publications.html>

ABSTRACT

A novel approach to reducing the unbalance rotor loads by pitch control is presented in this paper. Each blade has its own actuator, sensors and controller. These localised blade control systems operate in isolation without need of communication with each other. This single blade control approach to regulation of unbalanced rotor loads has several advantages including being straightforward to design and easy to tune. Furthermore, it does not affect the operation of the central controller and the latter need not be re-designed when used in conjunction with the single blade controllers. Their performance is assessed using BLADED simulations.

Leithead WE, Neilson V and Dominguez S, *A novel approach to structural load control using intelligent actuators*, 17th Mediterranean Conference on Control and Automation, Thessaloniki, Greece, June 2009. <http://www.supergen-wind.org.uk/publications.html>

ABSTRACT

The recent trend towards large multi-MW wind turbines resulted in the role of the control system becoming increasingly important. The extension of the role of the controller to alleviate structural loads has motivated the exploration of novel control strategies, which seek to maximise load reduction by exploiting the blade pitch system. The reduction of blade fatigue loads through individual blade pitch control is one of the examples. A novel approach to reduction of the unbalanced rotor loads by pitch control is presented in this paper. Each blade is equipped with its own actuator, sensors and controller. These local blade control loops operate in isolation without a need of communication with each other. The single blade control approach to regulation of unbalanced rotor loads presented in this paper has an important advantage of being relatively easy to design and tune. Furthermore, it does not affect the operation of the central controller and the latter need not be re-designed when used in conjunction with the single blade controllers. Their performance is assessed using BLADED simulations.

Other publications

Two other papers related to materials are listed.

Berketis K and Hogg PJ, (2007) *Impact response of composites after long-term water immersion*, Journal of Material Science, Vol. 42, No 16, pp 6642-6650.

Online access: <http://dx.doi.org/10.1007/s10853-007-1520-2>

ABSTRACT

Woven and non-crimped glass fabric reinforced polyester flat composite plates are studied experimentally. Water immersion tests for undamaged and impact damaged specimens are performed. The accelerating effects of increased water temperature on the degradation rate are discussed. The effect of up to 30 months water immersion on the impact behaviour are extensively investigated and compared with pre-water immersion results. The effects of different E-glass fabric reinforcement types, woven and non-crimped, in terms of environmental and impact behaviour are reported. An Environmental Damage Accumulation Metric (EDAM) is proposed and analysed, linking the time of water immersion with a marked change of behaviour in terms of the loss of the elastic component during the impact event.

Berketis K, Tzetzis D and Hogg PJ, (2008) *The influence of long term water immersion ageing on impact damage behaviour and residual compression strength of glass fibre reinforced polymer (GFRP)*, Materials & Design, Vol. 29, Issue 7, pp 1300-1310. Online access: <http://dx.doi.org/10.1016/j.matdes.2007.07.008>

Online access: <http://dx.doi.org/10.1016/j.matdes.2007.07.008>

ABSTRACT

Matrix and fibre/matrix interfacial degradation are end-effect characteristics of glass fibre composites subjected to water for very long periods. The performance of these materials to an external impact in a deteriorated condition and the associated residual strength are difficult to predict and usually accelerated tests are considered instead. This paper examines the durability of an isophthalic polyester resin reinforced with non-crimp glass fabrics in a hydrothermal environment (water baths at 65 °C) for up to 30 months. Water uptake measurements were conducted initially to investigate the degradation profiles of glass fibre composite plates after being permeated by water.

Matrix dissolution and interfacial damage appeared on the specimens following prolonged immersion while the absorption behaviour was found typically non-Fickian. The weight of the composite plates initially increased due to water diffusion up to month 14 and thereafter decreased due to material losses. Impacting after the conditioning phase for various time intervals did not increase considerably the damage size but produced a greater density of through thickness damage, which resulted in a lower compression after impact (CAI) strength measured on a newly designed miniaturised CAI rig. The reductions in compression strength over time tent to reach a minimum plateau after extended exposure to water, irrespective of the applied impact energy, while the dominant mechanism causing failure seemed to be the prolonged immersion to water rather than the level of delamination, introduced by the applied impact loading.

4.5 Theme Z: Environmental issues

Theme leader: University of Strathclyde

Partners: Manchester University
Manchester Metropolitan University

4.5.1 Introduction

Offshore wind farms cover large areas of open water making them potential hazards to navigation and highly exposed to the danger of lightning strikes. Investigation into the interference by wind farms with ships' radar has confirmed that there may be an impact on radar producing spurious returns on displays caused by multiple reflections, as well as beam spreading and side-lobe detection due to the very high radar cross section of the wind turbine. A number of potential sites are considered to be close to or encroach into waters with a high density of shipping movements or waters used by fishing vessels and recreational craft. The sea conditions also make the tower foundations susceptible to scour processes which may degrade the quality of the foundation with time. The research in Theme Z is looking into these environmental issues related to wind turbines.

4.5.2 Research outputs

The research outputs are grouped by three research topics in this theme.

Foundation scour

For investigating foundation scour, one paper is concerned with extending and validating a hydrodynamic model and in particular with developing a suitable turbulence model. The resulting model will be coupled to a sediment transport model in a later work package prior to scour simulation. Another paper describes the experimental study of foundation scour.

Bai, W, Mingham CG, Causon DM and Qian, L, (2009) *Finite volume simulation of viscous free surface waves using the Cartesian cut cell approach*, International Journal for Numerical Methods in Fluids, Vol. 63, Issue 1, pp 69-95.

Online access: <http://dx.doi.org/10.1002/flid.2079>

INTRODUCTION

The Navier-Stokes and Euler equations have been solved for simulating the flows with and without free surfaces by using a finite volume method with the application of the Cartesian cut cell approach. In the cut cell approach, generally speaking, the choice of the background grid is arbitrary: any existing grid systems can be applied in generating a cut cell mesh, but the Cartesian grid adopted here is the simplest one among others. Therefore, in principle, any existing flow solvers developed for any grid systems can be extended conveniently to adopt the cut cell approach. No lots of additional works are required, only to introduce corresponding boundary conditions in the cut cells is necessary, which means the existing programs can be utilized in a maximum degree. The cut cell approach is particularly suitable for extending the existing flow solvers to investigate moving boundary problems, such as free surface flows and fluid-body interactions. In this paper, many numerical results obtained by using the present model have been shown. The comprehensive comparisons with the experimental data and the analytical solutions indicate that this numerical model is very powerful, efficient and convergent fast, especially for the complicated moving boundary problems. However, it should be mentioned that due to the use of merged cells in the numerical model, sometimes relatively larger numerical errors become apparent after a long time accumulation: these possibly can be avoided by using a finer mesh in the region where a detailed velocity field needs to be described.

The current 2D flow solver presented here has already been extended to the 3D version by generating the cut cell mesh on the horizontal plane with extending them vertically. The traditional LES turbulence model is employed, based on this 3D flow solver, to simulate the turbulent flows around square and circular cylinders. However, the non-affordable computational cost of LES turbulence model in the attached boundary layer flows and the limitations of the RANS turbulence model in the predictions of separating regions at high Reynolds numbers inspired the introduction of hybrid turbulence models combining the advantages of both the RANS and LES models. The leading hybrid model is DES, which is also studied. This research is progressing well and has enabled us to generate many insightful results which are beginning to be published.

McGovern D, Ilic S, Folkard A, McLelland S and Murphy B, *Flow and turbulence around an Offshore Wind Turbine Pile in Tidal Currents using Particle Image Velocimetry*, Proceedings Coastal Dynamics '09, Tokyo, 7th – 11th September 2009.

ABSTRACT

The three-dimensional spatial characteristics of velocity and turbulence of tidal flow around an offshore wind turbine model have been measured using the technique of Particle Image Velocimetry, (PIV). This approach allows for the instantaneous velocity measurement in large volumes of water. This paper presents analysis of velocity and turbulence parameters in the wake flow behind a cylinder for different tidal stages. The wake flow behind a cylinder is highly complex making it difficult to characterise using point measurement techniques in the laboratory, and model numerically. The PIV measurements enabled the derivation of detailed velocity vector maps, turbulence intensities, kinetic energy and Reynolds stresses across the water column. Results showed a clear flow separation zone between reversed and stream-wise flow in the wake, the structure of which depends on flow velocity and water depth.

Radar Cross Section, lightning protection, and wind farm radar model

Two major threats to the continued development of wind power are the performance impact that wind farms have on radar and the risk that lightning poses to the integrity of the wind turbine. This unique piece of work in the project addresses both issues in a coherent manner with the impact of the lightning protection system design on the radar cross-section considered. Research outputs in the topic include four papers and three reports.

Peesapati V and Cotton I, *Lightning protection of wind turbines – a comparison of lightning data and the IEC 61400 - 24*. 1st Int Conf on Sustainable Power Generation and Supply, Nanjing, China, April 2009. <http://www.supergen-wind.org.uk/publications.html>

ABSTRACT

IEC 61400–24 dealing with lightning protection of wind turbines was first introduced in 2002. This was initially developed as a technical report. Since then, wind power has been rapidly developing with wind turbine manufacturers developing larger wind turbines which are at an increased risk of lightning strikes. With the move of large wind farms offshore, maintenance of wind turbines also becomes harder owing to the harsh and unpredictable environment. Limiting lightning strike damage on wind turbines becomes even more important. The IEC technical report has recently been developed into a full standard by the committee. The test levels (at which components should be tested) stated in the standard are based on those presented in IEC 62035 – Protection against Lightning. The present paper discusses the relevancy of the test levels in comparison to actual lightning strike data gathered from different wind farms of the world.

Peesapati V and Cotton I, *Lightning protection of wind turbines – a comparison of real lightning strike data and finite element lightning attachment analysis*, 1st International Conference on Sustainable Power Generation and Supply (SUPERGEN), Nanjing, China, April 2009. Online access: <http://www.supergen-wind.org.uk/publications.html>

ABSTRACT

Wind turbine lightning protection systems have been developed to the point where lightning damage is relatively rare. However, with windfarms moving offshore, manufacturers are striving to continuously improve lightning protection systems while ensuring that they comply with relevant IEC standards. The case of offshore wind farms is particularly important due to the difficulties faced in accessing a wind turbine should this be required owing to lightning damage. The paper details work done to model upward propagating lightning strike attachment on a wind turbine. A 3D electrostatic model of a full scale wind turbine has been modelled using available Finite Element Analysis software. This full scale model is subjected to high electric fields comparable to those created by a charged cloud. Results from these simulations are then compared with those found from analysis of real lightning strike data taken from wind turbines and windfarms across the world.

Peesapati V, Cotton I, Sorensen T, Kokkinos N, and Krogh T, *Lightning Protection of Wind Turbines – A Comparison Of Measured Data With Required Protection Levels*, paper submitted to IET Renewable Energy Journal. <http://www.supergen-wind.org.uk/publications.html>

ABSTRACT

Since the 1990's, wind turbine lightning protection systems have been refined to the point where lightning damage is now relatively rare. This is increasingly important as wind turbines move offshore where access for maintenance is more difficult than for most land based windfarms. Manufacturers have been trying to make sure that the lightning protection systems they install comply with the highest protection levels stipulated in the relevant IEC standards. In this paper, data from the Nysted Offshore Windfarm in Denmark and that from a large number of other wind turbines worldwide is reviewed to show the range of lightning currents that have been measured on wind turbines currently in operation. These current values are compared with the required protection levels within the standards.

Rashid L, Brown AK, Peesapati V, and Cotton I, (2009) *DZ.2.1 Comparative analysis of the reliability of designs of lightning protection system versus the prospective radar visibility (RCS)*, SUPERGEN Wind deliverable report.

Online access: <http://www.supergen-wind.org.uk/members/members.html>

INTRODUCTION

The interference of wind farms with aviation and marine radar is considered a significant concern to the regulating authorities. In the UK, strict rules concerning the radar interference have caused planning applications to be rejected, modified or significantly delayed.

The interference due to the rotating blades and the large reflection of the radar signal has been well reported and explained. The main cause of concern is the large Radar Cross Section (RCS) of the wind turbines and the Doppler frequency shift caused by the rotating blades. Some filtering and advanced processing algorithms have been introduced as upgrades to the existing radar systems to reduce the effect on the system. However, these measures are still unable to completely resolve the interference issues. This is partially due to the complexity of the interaction and the large RCS of the turbine.

In order to reduce the scattering from wind turbines, the use of shaping to the tower and nacelle and the application of RAM to the blades has been considered as a possible mitigation measure. This report will highlight the benefits and possible issues and limitations when applying RAM to the blades such as the reduction of the lightning protection systems efficiency. It will present RCS modelling results of RAM treated 40 meter blade using the WinR model. WinR (Wind turbine RCS) is an RCS modelling tool developed at the University of Manchester (see report D.Z 2.5).

In addition to introducing the RAM solution on to the wind turbine blades, the report will investigate the effect of the RAM solution on the existing lightning protection system inbuilt in most megawatt turbine blades. Wind turbine blades are known to be prone to lightning attachment due to their large sizes and installation locations. These blades are usually made of glass fibre composite, thus are virtually non conductive.

The lightning protection system on the blade introduces a metal path for the safe conduction of the lightning current. In the absence of the lightning protection system the lightning current poses a serious threat to the wind turbine blades. Thus it is very important that the conductive elements present in the RAM solution do not affect the efficiency of the lightning protection system.

Rashid L, Brown AK, Peesapati V, and Cotton I, (2009) DZ.2.4 Report on Radar Cross Section & Lightning Protection, SUPERGEN Wind deliverable report.

Online access: <http://www.supergen-wind.org.uk/members/members.html>

INTRODUCTION

Large onshore turbines and offshore wind farm technology is expected to make a significant contribution to meeting the UK Government target of 10 per cent of the country's electricity needs through renewable sources by 2010 (the *Renewable's Obligation*). However, a significant proportion of new and existing wind farm planning applications submitted to regional agencies for consideration have objections raised to them on the basis of the potential for radar interference.

The interference of wind farms with aviation and marine radar is considered a significant concern to the regulating authorities. In the UK, strict rules concerning the radar interference have caused planning applications to be rejected, modified or significantly delayed.

The interference due to the rotating blades and the large reflection of the radar signal has been well reported and explained [1, 2, 3]. The main cause of concern is the large Radar Cross Section (RCS) of the wind turbines and the Doppler frequency shift caused by the rotating blades. Any radar mitigation solution must successfully address the three key issues, which are also referred to as "the three kings":

1. Successful detection of vessels within/above the wind farm (90% Probability of Detection)
2. Successful detection of real targets (ie, not false detection of wind turbines)
3. Detection must be positioned accurately (ie. No track seduction)

Some filtering and advanced processing algorithms [4, 5] have been introduced as upgrades to the existing radar systems to reduce the effect on the system. However, these measures are still unable to completely resolve the interference issues [6]. This is partially due to the complexity of the interaction and the large RCS of the turbine.

Another mitigation measure is the installation of an additional radar system to compensate the performance degradation. This can be achieved by positioning the second radar so that the area above the turbines is illuminated but not the wind farm itself. That way, aircrafts that are flying over the wind farm can be successfully detected by fusing the data from both radars. This has been a successful solution for the Glasgow and Kincardine Airports. However, in the case of maritime surveillance and navigation, this solution may not be practical, since the wind farm area needs to be illuminated as well.

Since the interference occurs due to the large RCS of the tower, nacelle and blades, the use of shaping to the tower and nacelle and the application of RAM to the blades has been considered as a possible mitigation measure [7, 8] to reduce the scattering from wind turbines.

Rashid L and Brown AK, (2009) DZ2.5 Report on Wind Farm Radar Cross Section, SUPERGEN Wind deliverable report.

Online access: <http://www.supergen-wind.org.uk/members/members.html>

INTRODUCTION

Offshore wind farm technology is expected to make a significant contribution to meeting the UK Government target of 10 per cent of the country's electricity needs through renewable sources by 2010 (the *Renewable's Obligation*). However, a significant proportion of new and existing wind farm planning applications submitted to regional agencies for consideration have objections raised to them on the basis of the potential for radar interference.

The majority of planning applications for "Round 1" wind farm sites were submitted in the late 1990's to 2000. Many of these were for relatively small numbers of what are now considered to be smaller turbines, predominantly onshore or coastal based due to the additional generating costs of remote offshore development. Despite this, a number of sites either remain at the planning stage or have since been abandoned following planning objections raised on the basis of microwave radar or communications interference.

Similarly, many current "Round 2" applications, usually for larger wind farms with larger turbines, typically located offshore, have objections lodged to their applications for planning due to radar interference concerns.

It is anticipated that given the limited number of sites in the UK suitable for the construction of wind turbines not in areas covered by radars, and the UK government's drive to increase the fraction of energy generated from renewable sources to 10% by 2010 the problem of objections on the basis of radar interference is set to become increasingly acute.

Interaction of structural, lightning protection & RCS issues

Peesapati V Rashid L, Jamshidi P, Cotton I, Brown A and Hogg, P, *Resolving performance conflicts between radar absorbing materials, lightning protection and cost-effective structural performance in new wind turbine blade designs*, EWEC2009, Marseille, France, March 2009. Online access: <http://www.supergen-wind.org.uk/publications.html>

ABSTRACT

This paper considers the various conflicts that arise in designing a wind turbine blade which satisfies the needs for enhanced structural performance and effective lightning protection whilst simultaneously providing a low radar cross section. Some novel materials solutions to these three problems are presented and empirical data will be used to develop routes to optimising the various properties provided. A key factor will be the ability to incorporate any potential solution within a low cost manufacturing system without introducing any significant weight penalty to the final manufactured blade. This work was funded by EPSRC under its SUPERGEN initiative.

5 PHASE 2 RESEARCH

Phase II of the SUPERGEN Wind will be launched in March 2010, which will concentrate on an integrated, cost-effective, reliable & available Offshore Wind Power Station, with the following Mission:

“To undertake research to achieve an integrated, cost-effective, reliable & available Offshore Wind Power Station.”

And the following four key areas:

- Reliability
- Resource estimation
- Scaling up of turbine size
- Lifetime costs

More information will be available online <http://www.supergen-wind.org.uk/>

APPENDICES

Appendix A Consortium

The SUPERGEN Wind Consortium is led by Strathclyde and Durham Universities and consists of 9 research groups with expertise in wind turbine technology, aerodynamics, hydrodynamics, materials, electrical machinery & control, and reliability & condition monitoring. The Consortium has the active support of 10 industrial partners, including wind farm operators, manufacturers and consultants.

A.1 Academic partners

- Institute for Energy and Environment
University of Strathclyde
Prof. W E Leithead
- New and Renewable Research Group
Durham University
Prof. P J Tavner
- Energy Research Unit
Rutherford Appleton Laboratory (RAL)
Science & Technology Facilities Council
Dr A G Dutton



Science & Technology Facilities Council
Rutherford Appleton Laboratory

- Centre for Renewable Energy Systems Technology
Loughborough University
Dr S Watson
- Communication Group
University of Manchester
Prof. A Brown
- Electrical Energy and Power Systems Group
University of Manchester
Dr I. Cotton
- Power Conversion Group
University of Manchester
Prof. A Smith
- Northwest Composite Centre
University of Manchester
Prof. P Hogg



- Centre for Mathematical Modelling and Flow Analysis
Manchester Metropolitan University
Prof. C Mingham
- EnFlo Laboratory,
University of Surrey
Dr P Hancock



A.2 Industrial partners

- AMEC Wind Energy 
- Areva T&D UK Ltd. 
- Econnect Ltd. 
- E.ON UK 
- ESR Network
- Garrad Hassan & Partners Ltd. 
- HR Wallingford Ltd. 
- New & Renewable Energy Centre Ltd. 
- QinetiQ 
- Romax 
- ScottishPower 
- Smart Fibres Ltd. 
- Vestas Blades Ltd 

A.3 Academic and industrial collaboration

The figure below shows the collaboration between academia and industry partners in different research area of SUPERGEN Wind.

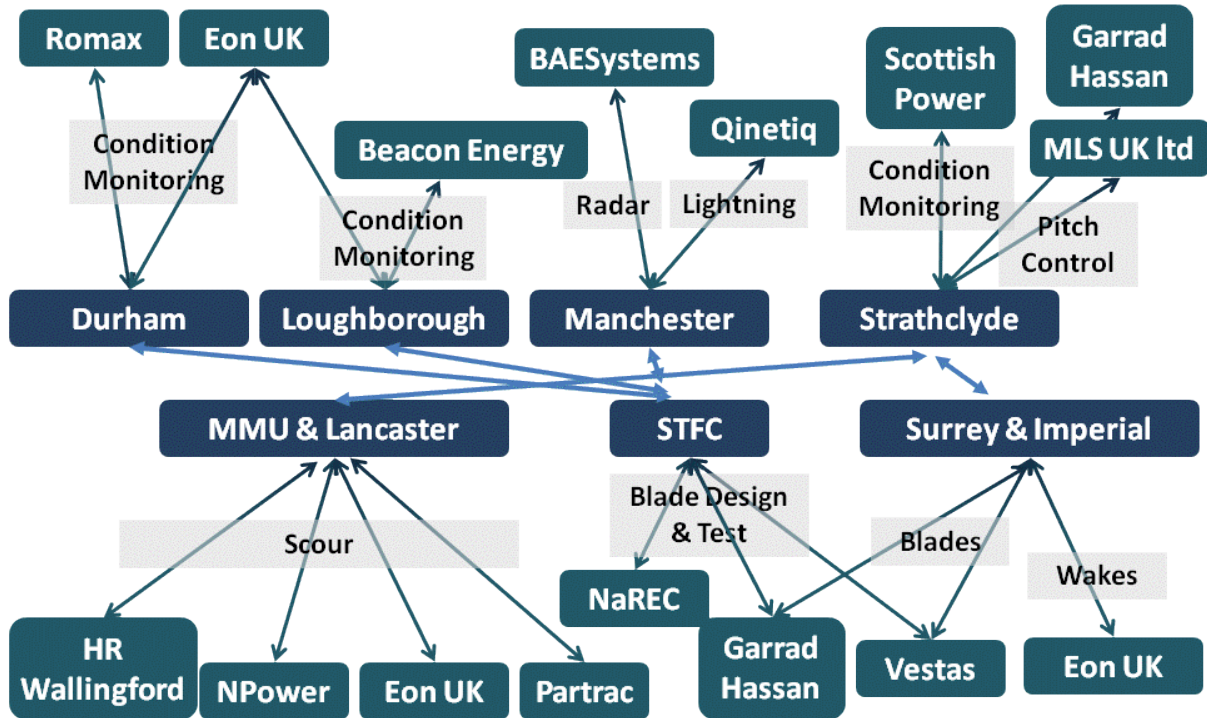


Figure 7 Academic and industrial collaboration

Appendix B Publications by author alphabetic order

B.1 Books

Leithead WE, (2007) *Chapter 5 Wind Energy*, Energy... beyond oil, Eds: Fraser Armstrong and Katherine Blundell, doi: ISBN-10: 0199209960, Oxford, PP 71-83.

Tavner PJ, Ran L, Penman J and Sedding H, *Condition Monitoring Of Rotating Electrical Machines*, IET, Stevenage, ISBN 978-0-86341-741-2, 2008.

B.2 Journal papers

Bai W, Mingham CG, Causon DM and Qian L, (2010), *Finite volume simulation of viscous free surface waves using the Cartesian cut cell approach*, International Journal for Numerical Methods in Fluids, Vol. 63, Issue 1, pp 69-95.

Berketis K and Hogg PJ, (2007) *Impact response of composites after long-term water immersion*, Journal of Material Science, Vol. 42, No 16, pp 6642-6650.

Berketis K, Tzetzis D and Hogg PJ, (2008) *The influence of long term water immersion ageing on impact damage behaviour and residual compression strength of glass fibre reinforced polymer (GFRP)*, Materials & Design, Vol. 29, Issue 7, pp 1300-1310.

Coolen FPA, Spinato F and Venkat D, (2008) *On modelling of grouped reliability data for wind turbine*, IMA Journal of Management Mathematics, published online on July 11, 2008.

Djurovic S, Williamson S and Renfrew A, (2009) *Dynamic model for Doubly-Fed Induction Generators with unbalanced excitation, both with and without winding faults*, IET Electric Power Applications, Vol. 3, No 3, pp 171-177.

Dutton AG, Bonnet PA, Hogg P and Lleon YL, (2010) *Novel materials and modelling for large wind turbine blades*, Journal of Power and Energy, Vol. 224, No 2, pp 203-210.

Feng Y, Tavner PJ and Long H, (2010) *Early Experiences with UK Round 1 Offshore Wind Farms*, accepted Proceedings of the Institution of Civil Engineers, Energy, 2010.

Gray CS and Watson S, (2009) *Physics of Failure Approach to Wind Turbine Condition Based Maintenance*, Wind Energy, Vol. 13, Issue 5, pp 395-405.

Guo H, Watson SJ, Tavner P and Xiang J, (2009) *Reliability analysis for wind turbines with incomplete failure data collected from after the date of initial installation*, Journal of Reliability Engineering and System Safety, Vol. 94, Issue 6, pp 1047-1063.

Leithead WE, (2007) *Wind energy*, Philosophical Transactions of the Royal Society A, Vol. 365, No. 1853, pp. 957-970.

Leithead WE and Dominguez S, (2007) *Active regulation of multi-MW wind turbines: an overview*, Power System Technology, Vol. 31, No. 20, pp. 24-34.

Leithead WE, (2008) *Supergen: Wind Energy Technologies*, UK Power Magazine.

Peesapati V, Cotton I, Sorensen T, Kokkinos N, and Krogh T, *Lightning Protection of Wind Turbines – A Comparison Of Measured Data With Required Protection Levels*, paper submitted to IET Renewable Energy Journal.

Polinder H, van der Pijl FFA, de Vilder GJ and Tavner PJ, (2006) *Comparison of Direct-Drive and Geared Generator Concepts for Wind Turbines*, IEEE Transactions on Energy Conversion, Vol. 21, No. 3, pp. 725-733.

Spinato F, Tavner PJ, van Bussel, GJW and Koutoulakos E, (2009) *Reliability of wind turbine subassemblies*, IET Renewable Power Generation, Vol. 3, No. 4, pp. 387-401.

- Tavner PJ**, Edwards C, Brinkman A and Spinato, F, (2006) *Influence of Wind Speed on Wind Turbine Reliability*, Wind Engineering, Vol. 30, No. 1, pp. 55-72.
- Tavner PJ**, Xiang J and Spinato F, (2007) *Reliability Analysis for Wind Turbines*, Wind Energy, Vol. 10, pp. 1-18. **TOP most-cited article in Wind Energy.**
- Tavner PJ**, (2008) *Review of condition monitoring of rotating electrical machines*, IET Electric Power Applications, Vol. 2, No. 4, pp. 215-247.
- Tavner PJ**, (2008) *Wind power as a clean-energy contributor*, Energy Policy, Volume 36, Issue 12, pp. 4397-4400.
- Tzetzis D** and Hogg PJ, (2008) *The influence of surface morphology on the interfacial adhesion and fracture behaviour of vacuum infused CFRP repairs*, Polymer Composites Volume 29, no 1, pp: 92-108.
- Tzetzis D** and Hogg PJ, (2008) *Experimental and finite element analysis on the performance of vacuum-assisted resin infused single scarf repairs*, Materials & Design, Volume 29, Issue 2, pp. 436-449.
- Watson SJ**, Infield DG, Barton JP and Wylie SJ, (2007) *Modelling of the performance of a building-mounted ducted wind turbine*, Journal of Physics: Conference Series 75 pp. 1-10.
- Watson SJ**, Xiang BJ, Yang W, Tavner PJ and Crabtree C, *Condition Monitoring of the Power Output of Wind Turbine Generators using Wavelets*, IEEE Transactions on Energy Conversion, Vol. 25, No. 3, pp.715-721.
- Yang WX**, Tavner P J and Wilkinson MR, (2009) *Condition monitoring and fault diagnosis of a wind turbine synchronous generator drive train*, IET Renewable Power Generation, Vol. 3, No. 1, pp. 1-11.
- Yang, WX**, Tavner, PJ, Crabtree, CJ and Wilkinson M (2010). *Cost-effective condition monitoring for wind turbines*, IEEE Transactions on Industrial Electronics. Vol. 57, No. 1, January 2010, pp. 263-271, ISSN: 0278-0046, DOI: 10.1109/TIE.2009.2032202

B.3 Conference papers

- Bampalas N** and Graham JMR, *Aerodynamic Rotor Model for Unsteady Flow and Wake Impact*, Wind Energy Colloquium, University of Oldenburg, Germany, 30th June - 2nd July 2008.
- Bonnet PA** and Dutton AG, *Parametric Modelling Of Large Wind Turbine Blades*, presented at Abaqus UK Regional User Meeting, November 2007.
- Bonnet PA** and Dutton AG, *Finite element modelling of blade thermoelastic stress analysis results*, European Wind Energy Conference (EWEC2008), Brussels, 31st March – 3rd April 2008.
- Bonnet P**, Dutton G, Court R, Ridley S, Jones H and Hope P, *Towards a more realistic fatigue loading for laboratory testing of wind turbine blades*, EWEC2009, Marseille, France, March 2009.
- Court RS**, Ridley S, Jones H, Bonnet PA and Dutton AG, *Fatigue testing of wind turbine blades with computational verification*, 17th International Conference on Composite Materials (ICCM-17), Edinburgh, UK, 27th – 31st July 2009.
- Crabtree CJ** and Tavner PJ, *Condition Monitoring of Wind Turbines*, 5th PhD Seminar on Wind Energy in Europe, Durham, 30th Sep – 1st Oct 2009.
- Crabtree CJ**, Feng Y, and Tavner PJ, *Detecting incipient wind turbine gearbox failure: a signal analysis method for on-line condition monitoring*, Proceedings EWEC 2010, Scientific Track, Oral Presentation, Warsaw, 20th – 23th Apr 2010.

- Crabtree** CJ, Djurovic S, Tavner PJ, and Smith AC, *Condition monitoring of a wind turbine DFIG by current or power analysis*. PEMD2010, Brighton, April 2010.
- Djurovic** S and Williamson S, *A coupled-circuit model for a DFIG operating under unbalanced conditions*, Proc. of the 2008 International Conference on Electrical Machines (ICEM 2008), Vilamoura, Portugal, September 2008.
- Djurovic** S and Williamson S, *Losses and pulsating torques in DFIGs with unbalanced stator and rotor excitation*, Proc. IEEE Int. Conf. on Sustainable Energy Technologies (ICSET2008), pp 328-333, Nov 2008.
- Djurovic** S, Williamson S, Tavner PJ and Yang WX, *Condition monitoring artefacts for detecting winding faults in wind turbine DFIGs*, European Wind Energy Conference and Exhibition (EWEC2009), Marseille, France, March 2009.
- Dominguez** S and Leithead WE, *Size related performance limitations on wind turbine control performance*, Proc. Control 2006, Glasgow, 2006.
- Dominguez** S and Leithead WE, *Control design toolbox for large-scale PRVS wind turbines*, Proceedings of the 2007 EWEA European Wind Energy Conference (EWEC2007), Milan. 7th – 10th May 2007.
- Dutton** AG, Bonnet PA, Hogg P and Kun L, *Novel materials and modelling for large wind turbine blades*, UKERC Sustainable Energy UK: Meeting the Science and Engineering Challenge, St Anne's College, Oxford, 13th – 14th May 2008.
- Garlick** WG, Dixon R and Watson SJ, *A Model-based Approach to Wind Turbine Condition Monitoring using SCADA Data*, ICSE 2009, Coventry, September 2009.
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