Optimising design, operation and maintenance for new generations of wind energy systems

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Executive Summary

ReliaWind project is funded under the umbrella of the European Union's 7th Framework Programme. Its main goal is to usher in a new generation of more efficient and reliable wind turbines, providing practical results to be used in wind turbine design, operations and maintenance. Ten partners collaborated in this project including Gamesa (project coordinator), ABB, Alstom Power Systems, Durham University, GL Garrad Hassan, Hansen Transmissions, LM Wind Power, Computer and Automation Institute of Hungarian Academy of Sciences (MTA SZTAKI), Relex and SKF.

The main purpose of this Monograph is to provide an overview of research results achieved in the ReliaWind between March 2008 and March 2011. During this period achievements have been made across different topics of the project, with a number of papers published in international journals and conferences.

In this monograph the ReliaWind project is briefly introduced in the Project Introduction with its objectives. The research outputs were categorised into four main areas:

- Field Reliability;
- Design for Reliability;
- Algorithms;
- Proof of Concept.

The Consortium is listed in Appendix A and a summary of the publications is given alphabetically by authors' surname in Appendix B.

Acknowledgement

The ReliaWind project was established by the European Commission, within the frame of the European Union's Seventh Framework Programme for RTD (FP7) under the Specific Programme COOPERATION, Theme 5 – Energy (Call FP7-ENERGY-2007-1_RTD) in 2008.

The Consortium would like to express their sincere appreciation to the European Commission for their support in research carried out in ReliaWind.

They also acknowledge the support and help provided by their partners, which include Gamesa (project coordinator), ABB, Alstom Power Systems-Wind (previously Ecotecnia), Durham University, GL Garrad Hassan (previously Garrad Hassan and Partners), Hansen Transmission International, LM Wind Power (previously LM Glasfiber), MTA SZTAKI, Relex Reliability Software and Services, and SKF.

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Project Introduction

RELIAWIND is the first-ever European project that brings together major stakeholders of the complete Wind Energy value chain in order to jointly develop tools, models and design guidelines that will set the grounds for an upcoming new generation of highly cost effective Wind Turbines.

From March 2008 to March 2011, RELIAWIND consortium, for the first time in the European Wind Energy Sector, and based on successful experiences from other sector (e.g. aeronautics) has jointly and scientifically studied the impact of reliability changing the paradigm of how Wind Turbines and designed, operated and maintained.

The Project's main goal is to usher in a new generation of more efficient and reliable wind turbines, providing practical results to be used in wind turbine **design**, **operations and maintenance**, with the following objectives:

- Obtaining a greater knowledge on the way Wind Turbine and its components behave from a reliability point of view.
- Checking that the knowledge that every manufacture has of the way components behave from a reliability point of view is close to reality and, if not, to pursue its convergence.
- Producing design, operations and maintenance guidelines that, when implemented, will reduce O&M costs and change completely the wind energy current economic paradigm.

To this end, the project proposes architecture directed at a modular design more immune to environmental conditions, permitting the replacement of components simply and quickly; to improve monitoring systems for components and thus achieve more accurate diagnosis; and to develop preventive maintenance algorithms for failure anticipation. These new technologies will be integrated into future generations of wind turbine components, wind turbines and wind farms.

Research outputs from four main areas, i.e., Field Reliability Analysis, Design for Reliability, Algorithms, and Proof of Concept, are listed in the subsequent four sections.

WP-1: Field Reliability Analysis

Within any complex system, certain components will stand out as high-risk items, either because they are 'weak points' that are failure prone, or are absolutely essential for 'normal' turbine operation, or are expensive and time-consuming to diagnose and repair.

The aim is to capture, collect, and analyze historical wind farm Supervisory Control and Data Acquisition (SCADA) datalogs and maintenance data from several sources available to the project partners to determine which components and failure modes should be subject to a more detailed work during next project phases.

Therefore, based on an empirical analysis, this WP has determined and identified the 'high risk items' and failure modes.

Guo, H, Watson, S, Tavner, PJ and Xiang, J (2009). ***"Reliability analysis for wind turbines with incomplete failure data collected from after the date of initial installation"***, Reliability Engineering & System Safety 94(6): 1057-1063. 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.

Spinato, F, Tavner, PJ, van Bussel, GJW and Koutoulakos, E (2009). ***"Reliability of wind turbine subassemblies"***, IET Proceedings Renewable Power Generation 3(4): 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 (2008). ***"Wind power as a clean-energy contributor"***, Energy Policy 36(12): 4397-4400. Online access: http://dx.doi.org/10.1016/j.enpol.2008.09.033

ABSTRACT
Modern and sophisticated wind generators rated at up to 5 MW are in use on- and offshore in many European and other countries. They are made by a large and financially strong industry. In 2006, there were 1672 wind turbines in use in the UK, making up 2.5% of UK's electricity-generating capacity but producing under 1% of its electricity. The UK uses only about 1% of its wind power potential. Making use of more wind will involve developing new materials, new techniques and new mathematical modelling methods. The machines will need to be more reliable and robust, and will require a more flexible electricity system to feed into. In the longer term, there may be bigger machines of up to 10 MW, perhaps used in tandem with advanced electricity-storage technology. The growth of a European rather than UK power grid may allow renewables, including wind, to play a larger role.

Feng, Y, Tavner, PJ and Long, H, ***"Early Experiences of UK Round 1 Offshore Wind Farms"***, Proceedings of the Institution of Civil Engineers, 163(4): 167–81. Online access http://dx.doi.org/10.1680/ener.2010.163.4.167

ABSTRACT
The UK government plans that offshore wind power should play a major part in meeting the UK's renewable energy and carbon emission targets by 2020. The pioneer UK round 1 offshore wind farm projects, based on sites let in 2001, were supported by the UK Department of Trade and Industry's 'Offshore wind capital grants scheme'. Round 2 offshore sites were let in 2003 and the successful bidders for round 3 offshore sites were announced in January 2010; therefore the published reports from round 1 could provide valuable information on offshore experiences for the operation of later rounds. This paper reviews the performances of those UK round 1 offshore wind farms during their early operation based on published reports from the 'Offshore wind capital grants scheme' available for the period 2004–2007 and early operational issues. UK round 1 offshore wind farms have achieved an average cost of energy of £69 per MWh, in line with expectations, but at 80·3% the average availability fell short of expectations. The availability of UK round 1 offshore wind farms has been shown to decrease with increasing wind speed therefore it is recommended that improvements of availability at wind speeds of 7–14 m/s will be needed to meet more ambitious economic targets.

Elkinton, C, Wilkinson, M and Harman, K (2009). "*Derivation of Wind Turbine Reliability Profiles from Operational Data*". EWEC2009, Marseilles, France, March. Online access: http://www.reliawind.eu/project-wind-energy/reliawind-main-publications

ABSTRACT
This poster describes on-going work to derive wind turbine Reliability Profiles, showing the failure rate and downtime broken down by each subassembly. Historical operational data available to wind farm operators include 10-minute SCADA, automated fault logs and Operations and Maintenance reports. Processes have been developed to link these discrete and diverse data formats.

The results will allow the comparison between wind turbine subassemblies and, as more data is added, will permit wind farm owners and operators to compare their machines from one wind farm against others of a similar type in a different wind farm.

The work described here forms part of initial work undertaken in the Reliawind project, which is a European Union 7th Framework Integrated Project with an overall budget of $11M. The 10 industrial and academic partners include wind turbine manufacturers, major component manufacturers, renewable energy consultants and research institutions.

Feng, Y, Tavner, PJ, Long, H and Bialek, J "*Review of Early Operation of UK Round 1 Offshore Wind Farms*", presented at IEEE PES 2010 General Meeting, USA, 2010. Online access: http://www.reliawind.eu/project-wind-energy/reliawind-main-publications

ABSTRACT
The UK Government plans that offshore wind power should play a major part in meeting the UK's renewable energy and carbon emission targets by 2020. The pioneer UK Round 1 offshore wind farm projects, based on sites let in 2001, were supported by the UK Department of Trade and Industry's "Offshore Wind Capital Grants Scheme". This paper reviews the economic and operational performances of those farms based on published reports available for the early period 2004-2007. UK Round 1 offshore wind farms have achieved an average Cost of Energy of £69 per MWh, in line with expectations, but at 80.3% the average availability has fallen short of expectations. The availabilities have been shown to decrease with increasing wind speed. Improving the availabilities at high wind speeds is key to meet the more ambitious economic targets, particularly for future Rounds 2 and 3.

Garrad Hassan & Partners, Gamesa, Alstom Ecotecnia, Durham University, "*Methodology and Results of the Reliawind Reliability Field Study*", Scientific Track, European Wind Energy Conference, Warsaw, 2010. Online access: http://www.reliawind.eu/project-wind-energy/reliawind-main-publications

ABSTRACT
The EU FP7 Reliawind project has the aim to identify and understand critical failures and their mechanisms through quantitative studies of detailed wind farm data. A common wind turbine taxonomy and a universal database structure for storing downtime events from multiple manufacturer's turbines have been defined. Systematic and consistent processes have been developed to deal with historical data from wind farm Owners and Operators. Data including 10-minute SCADA, service records/work orders and alarm logs have been analysed to determine downtime events within the common taxonomy. The downtime events have been analysed to determine the distribution of failure rates and downtimes between the sub-assemblies. To-date 31,500 downtime events have already been added to the common database structure and the database is still under expansion.

Tavner, PJ, Spinato, F, Bussel, GJWv and Koutoulakos, E (2008). "*Reliability of different wind turbine concepts with relevance to offshore application*". EWEC2008, Brussels, April. Online access: http://www.reliawind.eu/project-wind-energy/reliawind-main-publications

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, Gindele, R, Faulstich, S, Hahn, B and Whittle, MWG "*Study of Effects of Weather & Location on Wind Turbine Failure Rates*", European Wind Energy Conference, Warsaw, 2010. Online access: http://www.reliawind.eu/project-wind-energy/reliawind-main-publications

ABSTRACT
Understanding the availability of wind turbines (WT) is vital to maximise WT energy production and minimise the payback period. Previous work tended to concentrate on the location of unreliability or failure modes in a WT. This paper investigates the influence of weather and location on WT failure rate and downtime, to understand the root causes and consequences of failure. The paper furthers a previous study covering the whole of Denmark by considering a limited population of identical WTs, located at 3 disparate German sites, using data extracted from the WMEP programme and local weather data, thereby focusing more precisely than previously.

The WMEP and associated weather data were analysed to find the WT failures and weather conditions and then cross-correlate them. The reliability characteristics of the WT populations followed the average t rends of the WMEP survey. Annual periodicity was found in the weather data but not in individual WT population failures. However, a strong cross-correlation can be seen between failures and weather data. This cross-correlation appears stronger than found in the earlier, larger study, vindicating our more focused approach.

It is clear that Operation and Maintenance has an impact on WT downtime and will be more important offshore. This work may indicate how weather may affect the availability of offshore WTs.

Wilkinson, M, Harman, K, Tavner, P and Hendriks, B (2009). "Derivation of wind turbine reliability profiles from operational data". EWEC2009, Marseille, March. Online access: http://www.reliawind.eu/project-wind-energy/reliawind-main-publications

ABSTRACT
This poster describes on-going work to derive wind turbine Reliability Profiles, which show the failure rate and downtime broken down by each subassembly. Historical operational data available to wind farm operators include 10-minute SCADA, automated fault logs and Operations and Maintenance reports. Processes have been developed to link these discrete and diverse data formats.

The results will allow the comparison between wind turbine subassemblies and, as more data is added, will permit wind farm operators to compare their machies from one wind farm against others of a similar type in a different wind farm.

WP-2: Design for Reliability

Understanding the failure modes, their mechanisms and the physical and chemical magnitudes and variables that are involved in the phenomena allows scientists to construct logical models of failure mode growth and propagation, both in two scenarios: Within the WTG architecture and along time. These reliability models will contribute to the main project objectives in two ways: 1) Design for Reliability and 2) Condition Monitoring. Each industrial partner will construct in a coordinated fashion its applicable subsystems and component functional and reliability models and one SME partner, acting as model integrator, will assemble all previous "building blocks" in order to attain a complete full WTG reliability model.

Deliverables of this WP are expected to be the selection and specification of appropriate sensing devices for capturing the aforementioned physical and chemical magnitudes. Signals coming from these devices will later act as inputs to the logical algorithms defined in WP3.

Arabian-Hoseynabadi, H, Oraee, H and Tavner, PJ, *"Failure Modes and Effects Analysis (FMEA) for wind turbines"*, International Journal of Electrical Power & Energy Systems, 32(7): 817-824.
Online access: http://dx.doi.org/10.1016/j.ijepes.2010.01.019

ABSTRACT
The Failure Modes and Effects Analysis (FMEA) method has been used to study the reliability of many different power generation systems. This paper now applies that method to a wind turbine (WT) system using a proprietary software reliability analysis tool. Comparison is made between the quantitative results of an FMEA and reliability field data from real wind turbine systems and their assemblies. These results are discussed to establish relationships which are useful for future wind turbine designs.

The main system studied is an existing design 2 MW wind turbine with a Doubly Fed Induction Generator (DFIG), which is then compared with a hypothetical wind turbine system using the Brushless Doubly Fed Generator (BDFG) of the same rating.

The software reliability analysis tool used for these studies was Relex Reliability Studio 2007 Version 2.

Firth, A and Long, H "*A Design Software Tool for Conceptual Design of Wind Turbine Gearboxes*", European Wind Energy Conference, Warsaw, 2010. Online access: http://www.reliawind.eu/project-wind-energy/reliawind-main-publications

ABSTRACT
The paper reports the development of a design software tool for wind turbine gearboxes. It facilitates the conceptual design of wind turbine gearboxes supporting designs with different combinations of epicyclic and parallel gear stages. Analyses of gear bending strength and pitting resistance are in accordance with the AGMA2001 standard. The calculations of the AGMA geometry factors and are verified in accordance with the AGMA 908 information sheets. A case study of a 2MW and three phase asynchronous generator with a nominal rotational speed around 1600 rpm has been tested to demonstrate the capabilities of the design software tool.

Smolders, K, Long, H, Feng, Y and Tavner, PJ "*Reliability Analysis and Prediction for Wind Turbine Gearboxes*", Scientific Track, European Wind Energy Conference, Warsaw, 2010. Online access: http://www.reliawind.eu/project-wind-energy/reliawind-main-publications

ABSTRACT
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 Relex 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.

Tavner, PJ, Higgins, A, Arabian, H, Long, H and Feng, Y "*Use of the FMEA to Wind Turbine Availabilities*", European Wind Energy Conference, Warsaw, 2010. Online access: http://www.reliawind.eu/project-wind-energy/reliawind-main-publications

ABSTRACT
Failure Modes and Effects Analysis (FMEA) has been shown to be an effective way of improving machinery design reliability. This paper applies the FMEA to the design for availability of a 2MW, geared, exemplar R80 wind turbine design used in the EU FP7 ReliaWind Consortium.

The technique will be used to compare the prospective reliabilities of three versions of the geared R80 turbine with different drive train solutions. These solutions have been proposed to reduce overall wind turbine failure rate and raise its availability. The first solution incorporates a conventional LV Doubly Fed Induction Generator (DFIG) with partially-rated Electrical Converter and Transformer; the second solution incorporates an innovative Hydraulic Converter coupled to an MV Synchronous Generator (SG) and no Transformer; the third solution incorporates an innovative LV Brushless Doubly Fed Induction Generator (GDFIG) also with a partially-rated Electrical Converter and Transformer.

The paper proposes modifications to the FMEA method to analyse and compare reliabilities and applies that approach to these three alternative designs to identify their relative merits.

WP-3: Algorithms

All the results achieved during previous work packages will be integrated into a consistent set of tools and applications that can provide Condition Based Maintenance tools for wind turbines and wind farms. Existing protocols and standards for connectivity to current SCADA systems will be adopted and new extensions will be proposed to benefit from the findings of the project.

Deliverables of this WP are expected to be a consistent set of maintenance tools and the definition of specific software components to integrated in an extensible software framework to create a multi-agent software platform to simulate each possible turbine operational condition and WTG configuration to be modelled. An holistic wind farm software model (virtual demonstrator) is expected to be built and tested in order to verify and show the principles achieved by the project.

Yang, W, Tavner, PJ and Wilkinson, MR (2009). ***"Condition monitoring and fault diagnosis of a wind turbine synchronous generator drive train"***, IET Renewable Power Generation 3(1): 1-11.
Online access: http://dx.doi.org/10.1049/iet-rpg:20080006
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, W, Tavner, PJ, Crabtree, CJ and Wilkinson, MR (2010) ***"Cost-effective Condition Monitoring for Wind Turbines"***, IEEE Transactions on Industrial Electronics, 57(1):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.

Watson, SJ, Xiang, BJ, Yang, W, Tavner, PJ and Crabtree, CJ (2010) ***"Condition Monitoring of the Power Output of Wind Turbine Generators using Wavelets"***, IEEE Transactions on Energy Conversion, 25(3): 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 a variable-speed wind turbine generator 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 variable-speed 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 3 months before a bearing failure was recorded.

Crabtree, C, Feng, Y and Tavner, PJ "*Detecting Incipient Gearbox Failure in Wind Turbines: A New Signal Analysis Method for On-line Condition Monitoring*", Scientific Track, European Wind Energy Conference, Warsaw, 2010. Online access: http://www.reliawind.eu/project-wind-energy/reliawind-main-publications

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.

Djurovic, S, Williamson, S, Tavner, PJ and X., YW (2009). "*Condition monitoring artefacts for detecting winding faults in wind turbine DFIGs*". European Wind Energy Conference and Exhibition (EWEC2009), Marseille, France. Online access: http://www.reliawind.eu/project-wind-energy/reliawind-main-publications

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.

Watson, SJ, Xiang, JP, Yang, W, Tavner, PJ and Crabtree, CJ (2009). "*Condition monitoring of a wind turbine doubly-fed induction generator*". EWEC2009, Marseille, March. Online access: http://www.reliawind.eu/project-wind-energy/reliawind-main-publications

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.

Yang, W, Tavner, PJ, Crabtree, CJ and Wilkinson, M (2008). "*Research on a simple, cheap but globally effective condition monitoring technique for wind turbines*". International Conference on Electrical Machines, Vilamoura, Portugal, September. Online access: http://www.reliawind.eu/project-wind-energy/reliawind-main-publications

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, W, Tavner, PJ and Wilkinson, M (2008). "*Wind turbine condition monitoring and fault diagnosis using both mechanical and electrical signatures*". IEEE/ASME International Conference on Advanced Intelligent Mechatronics, Xi'an, China, 2-5 July. Online access: http://www.reliawind.eu/project-wind-energy/reliawind-main-publications

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, W, Tavner, PJ and Wilkinson, M (2008). "*Condition monitoring and fault diagnosis of a wind turbine with a synchronous generator using wavelet transforms*". IET 4th International Conference on Power Electrical Machines and Drives, York, UK. Online access: http://www.reliawind.eu/project-wind-energy/reliawind-main-publications

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, W, Jiang, JS, Tavner, PJ and Crabtree, CJ (2008). "*Monitoring wind turbine condition by the approach of empirical mode decomposition*". International Conference of Electrical Machines and Systems (ICEMS 2008), Wuhan, China, 17-20 Oct. Online access: http://www.reliawind.eu/project-wind-energy/reliawind-main-publications

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, W, Tavner, PJ and Crabtree, CJ (2009). "*An intelligent approach to the condition monitoring of large scale wind turbines*". EWEC2009, Marseilles, France, March. Online access: http://www.reliawind.eu/project-wind-energy/reliawind-main-publications

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.

WP-4: Proof of concept

All the results achieved during previous work packages will be integrated into a consistent set of tools and applications that can provide Condition Based Maintenance tools for wind turbines and wind farms. Existing protocols and standards for connectivity to current SCADA systems will be adopted and new extensions will be proposed to benefit from the findings of the project.

Deliverables of this WP are expected to be a consistent set of maintenance tools and the definition of specific software components to integrated in an extensible software framework to create a multi-agent software platform to simulate each possible turbine operational condition and WTG configuration to be modelled. An holistic wind farm software model (virtual demonstrator) is expected to be built and tested in order to verify and show the principles achieved by the project.

Viharos, ZsJ, Monostori, L, Erdos, G and Kovács, A. "*AI Supported Maintenance and Reliability System in Wind Energy Production*", European Wind Energy Conference, Warsaw, 2010. Online access: http://www.reliawind.eu/project-wind-energy/reliawind-main-publications

ABSTRACT
The paper describes the result of the research in the fields of supervision, failure detection and prognosis, control, maintenance planning and decision support performed for ensuring high level availability of wind turbines and wind farms. This activity is realized in the frame of the EU 7th Framework project ReliaWind: Reliability focused research on optimizing Wind Energy systems design, operation and maintenance: Tools, proof of concepts, guidelines & methodologies for a new generation. Wind turbines are relatively complex electro-mechanical systems, their smooth functioning is an important economical factor. The handling of this complexity is supported by various, applied artificial intelligence techniques and solutions as described in the paper.

Appendix A Consortium

Gamesa is a company specialized in sustainable energy technologies and one of the main wind turbine manufacturers worldwide. The company, which has over 13,000 MW installed throughout the world and 32 production centres in Europe, the USA and China, carries out the design, manufacturing, sales, installation, as well as operation and maintenance of its wind turbines. Its product portfolio comprises medium power turbines (Gamesa G5X-850 kW) and MultiMW turbines (Gamesa G8X-2.0 MW and the new platform under development: Gamesa G10X), whose main characteristics are an optimum adaptability to all types of sites and winds.

The Research and Development Department of **Gamesa**'s wind turbine manufacturing division works to develop new models, identify and oversee technological innovation projects in production processes and products, and provides technical support for the company's activities. The development and application of the most modern technologies is based on considerable investment in R&D. This has made Gamesa one of the top eight Spanish companies, and among the top 300 in Europe, in terms of investment in research and development.

Alstom Power Systems - Wind (previously Ecotecnia) is a Wind Turbine manufacturer, working in turbine design and production and Wind Farm engineering, construction, operation and maintenance, but is also present in the solar power production market. Though its headquarters are in Barcelona, it has 700 employees altogether and four industrial plants throughout Spain. It has been a Member of EWEA organization from its beginning, and has at present almost a 2% share of the global marke

It has been present in the Wind Power market since 1984, with more than 100 engineers experienced in all technologies involved in Wind energy. It will contribute to the project defining process and data requirements for reliability improvement and evaluation due its knowledge of design operation and maintenance and, even more with its experience of processes to interrelate these tree disciplines (transfer of know-how and feed-back).

LM Wind Power (previously LM Glasfiber) is the world's leading supplier of blades for wind turbines, and the only supplier that operates on a global basis. Blades play a crucial role in wind turbines and their design is crucial to the efficient exploitation of energy from the wind. LM blades are currently mounted on more than one in three wind turbines throughout the world. Our production capacity measured in MW is the largest in the industry, and we have factories in four major regions including Northern Europe, Southern Europe, North America and Asia.

Regarding the RELIAWIND project and needs for expertise, LM Wind Power is accredited to test wind turbine blades by DANAK – the Danish Accreditation and Metrology Fund. This accreditation from the official Danish body in this field is the seal of approval for impartiality, reliability and technical competence in the methods used in our testing and calibration laboratories. We carry out both static and dynamic tests on all new blades, and the results are then incorporated into our integrated test programme. In addition, LM Wind Power, use different kinds of electronic NDT to complement visual and manual quality assurance (QA).

Hansen Transmissions is a Belgian company and has 1400 employees worldwide. Hansen Transmissions designs, manufactures, sells and services innovative and durable drives for a wide range of industrial applications throughout the world, especially in sectors where low noise levels, minimum weight and high reliability are essential (including water treatment, wind-turbines, material handling, etc.). The company is continually investing in the latest technology and machinery.

Hansen is specialised in gear technology and design, gearbox design and validation testing, fatigue analysis, dynamical modelling and noise as well as vibration

ABB, located in Helsinki, Finland, specialises in development and manufacturing of low voltage drives and motors/generators and is recognized as market leader in frequency converter drives and in high power AC machines.

As manufacturer of wind turbine converter and electrical generators Drives contributes to the project with know-how of power electrical components to model reliability of electrical drive-train and to improve diagnostic.

SKF is a Swedish company celebrating its 100 year anniversary in 2007. The company was founded by a textile Engineer who was facing a reliability issue due to changing geological conditions beneath his factory. This led to the innovation of the self aligning ball bearing and the formation of the SKF company. Now in a new millennia SKF faces a new reliability challenge for a critically important form of renewable energy - wind energy. SKF is committed to making its contribution to improving this situation to benefit this industry and thereby reducing dependence on fossil fuels and hence CO2 generation. SKF is work leader in rolling element bearing manufacture and design. with manufacturing experience also extending to seals, housings and bespoke sub systems. Knowledge of application extends from design criteria to maintenance management, including condition monitoring.

GL Garrad Hassan is the leading independent engineering consultancy (nearly 300 engineers in 18 countries) providing expert advice to the wind industry for more than 20 years. The company has played a key role in proposing and successfully completing EU research projects and has considerable expertise and experience relevant to this Project including:

- Analysis and assessment of more than 80,000 MW of wind farms around the world, acting as Banks' or Owners Engineer for 21,000 MW (worth some £21 billion) of wind capacity;
- Experience of the derivation of reliability profiles of wind turbines represented in terms of mean time between failure (MTBF) and mean time to repair (MTTR) statistics;
- Experience of fault tree analysis and failure mode effects analysis (FMEA) for wind turbine systems;
- Experience of comprehensive load calculations, control system development, design of mechanical, structural and electrical components, support of certification and testing of both onshore and offshore wind turbines;
- Development of software models.

Relex' main task is the sale and technical support of analysis software package "Relex Reliability Studio 2007", which is the world's leading software tool as it contains modules for almost all reliability analysis methods. In addition RSCE performs consultancy work for various European companies mainly from the telecom, industrial electronics, defence and aerospace business. RSCE is specialized to perform reliability, safety analyses as well as risk assessments for all kinds of systems and equipment.

- Relex is going to bring its strong knowledge and experience in reliability to the other partners of the consortium, based on its past experience and European recognition:
- Reliability analyses are based on certain standards which have been developed for aerospace, electronics, public traffic and nuclear industry. Use of these methods can also improve reliability on Wind energy systems
- Relex, as a supplier of the main analysis tool, has gathered lot of experience and can transfer the knowledge gained from this by providing training to the individual partner companies. In addition Relex will act as an independent supervisor and perform the top-level analyses.

Durham University is England's 3rd oldest University is located in the North East close to Newcastle. Last year it was the UK University with the highest international citation level for its research work. The School of Engineering was the first established in the UK in 1838 and is recognised as one of the UK's 5 foremost Engineering Schools. The School has an integrated engineering research portfolio in which New & Renewable Energy is a flagship topic

The New & Renewable Energy research group's particular skill set is in the development of large-scale offshore wind and in particular the optimisation of reliability and availability of these systems. The skills of relevance to the project are the ability to predict turbine reliability and availability and the preparation of Failure Modes and Effects Analayses for renewable projects. Durham University has particular skills in the investigation of the reliability of wind turbines and their condition monitoring. They are members of the European Wind Academy and are connected to other researchers in the European Wind Industry.

The Computer and Automation Institute (**MTA SZTAKI**) was founded in the early 1960s as a research and development institution of the Hungarian Academy of Sciences. The Institute gained world-wide reputation in computer graphics, computer-aided design and manufacturing, process control, robotics, operations research, numerical methods, advanced information systems and networking. One of the main missions of the Institute is to realise technology transfer to the Hungarian industry and service sectors including SMEs.

Regarding the RELIAWIND project and its needs for expertise contributions will be provided by the Laboratory on Engineering and Management Intelligence (EMI) of SZTAKI as it is involved in research and elaboration of techniques applicable to handling complex production and business systems working in the uncertain, changing environments, with special emphasis on artificial intelligence and machine learning approaches, mainly in the fields of intelligent monitoring, supervision and control; modelling, control and optimization of technical and business processes; handling changes and disturbances in complex systems; modelling and simulation of large production and business systems.

Appendix B Publications by author alphabetic order

B.1 Journal papers

Guo, H, Watson, S, Tavner, PJ and Xiang, J (2009). *"Reliability analysis for wind turbines with incomplete failure data collected from after the date of initial installation"*, Reliability Engineering & System Safety 94(6): 1057-1063.

Spinato, F, Tavner, PJ, van Bussel, GJW and Koutoulakos, E (2009). *"Reliability of wind turbine subassemblies"*, IET Proceedings Renewable Power Generation 3(4): 387-401.

Tavner, PJ (2008). *"Wind power as a clean-energy contributor"*, Energy Policy 36(12): 4397-4400.

Yang, W, Tavner, PJ and Wilkinson, MR (2009). *"Condition monitoring and fault diagnosis of a wind turbine synchronous generator drive train"*, IET Renewable Power Generation 3(1): 1-11.

Yang, W, Tavner, PJ, Crabtree, CJ and Wilkinson, MR (2010) *"Cost-effective Condition Monitoring for Wind Turbines"*, IEEE Transactions on Industrial Electronics, 57(1):263-271.

Watson, SJ, Xiang, BJ, Yang, W, Tavner, PJ and Crabtree, CJ (2010) *"Condition Monitoring of the Power Output of Wind Turbine Generators using Wavelets"*, IEEE Transactions on Energy Conversion, 25(3): 715-721.

Feng, Y, Tavner, PJ and Long, H, *"Early Experiences of UK Round 1 Offshore Wind Farms"*, Proceedings of the Institution of Civil Engineers, 163(4): 167 –181.

Arabian-Hoseynabadi, H, Oraee, H and Tavner, PJ, *"Failure Modes and Effects Analysis (FMEA) for wind turbines"*, International Journal of Electrical Power & Energy Systems, 32(7): 817-824.

B.2 Conference papers

Crabtree, C, Feng, Y and Tavner, PJ "*Detecting Incipient Gearbox Failure in Wind Turbines: A New Signal Analysis Method for On-line Condition Monitoring*", Scientific Track, European Wind Energy Conference, Warsaw, 2010.

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

Elkinton, C, Wilkinson, M and Harman, K (2009). "*Derivation of Wind Turbine Reliability Profiles from Operational Data*". EWEC2009, Marseilles, France, March.

Feng, Y, Tavner, PJ, Long, H and Bialek, J "*Review of Early Operation of UK Round 1 Offshore Wind Farms*", presented at IEEE PES 2010 General Meeting, USA, 2010.

Firth, A and Long, H "*A Design Software Tool for Conceptual Design of Wind Turbine Gearboxes*", European Wind Energy Conference, Warsaw, 2010.

Garrad Hassan & Partners, Gamesa, Alstom Ecotecnia, Durham University, "*Methodology and Results of the Reliawind Reliability Field Study*", Scientific Track, European Wind Energy Conference, Warsaw, 2010.

Monostori L, Viharos ZJ, Erdős G, and Kovács A, (2009). "*AI supported maintenance and reliability system in wind energy production*", International Symposium on Methods of Artificial Intelligence, AI-METH, Gliwice, Poland, November 18-20.

Smolders, K, Long, H, Feng, Y and Tavner, PJ "*Reliability Analysis and Prediction for Wind Turbine Gearboxes*", Scientific Track, European Wind Energy Conference, Warsaw, 2010.

Tavner, PJ, Gindele, R, Faulstich, S, Hahn, B and Whittle, MWG "*Study of Effects of Weather & Location on Wind Turbine Failure Rates*", European Wind Energy Conference, Warsaw, 2010.

Tavner, PJ, Higgins, A, Arabian, H, Long, H and Feng, Y "*Use of the FMEA to Wind Turbine Availabilities*", European Wind Energy Conference, Warsaw, 2010.

Tavner, PJ, Spinato, F, Bussel, GJWv and Koutoulakos, E (2008). "*Reliability of different wind turbine concepts with relevance to offshore application*". EWEA European Wind Energy Conference, Brussels, April.

Viharos, ZsJ, Monostori, L, Erdos, G and Kovács, A. "*AI Supported Maintenance and Reliability System in Wind Energy Production*", European Wind Energy Conference, Warsaw, 2010.

Watson, SJ, Xiang, JP, Yang, WX, Tavner, PJ and Crabtree, CJ (2009). "*Condition monitoring of a wind turbine doubly-fed induction generator*". EWEC2009, Marseille, March

Wilkinson, M, Harman, K, Tavner, P and Hendriks, B (2009). "Derivation of wind turbine reliability profiles from operational data". EWEC2009, Marseille, March

Yang, W, Tavner, PJ and Wilkinson, M (2008). "*Condition monitoring and fault diagnosis of a wind turbine with a synchronous generator using wavelet transforms*". IET 4th International Conference on Power Electrical Machines and Drives, York, UK, 2-4 April.

Yang, W, Tavner, PJ, Crabtree, CJ and Wilkinson, M (2008). "*Research on a simple, cheap but globally effective condition monitoring technique for wind turbines*". International Conference on Electrical Machines, Vilamoura, Portugal, September.

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

Yang, W, Tavner, PJ and Wilkinson, M (2008). "*Wind turbine condition monitoring and fault diagnosis using both mechanical and electrical signatures*". IEEE/ASME International Conference on Advanced Intelligent Mechatronics, Xi'an, China, 2-5 July

Yang, W, Tavner, PJ and Crabtree, CJ (2009). "*An intelligent approach to the condition monitoring of large scale wind turbines*". EWEC2009, Marseilles, France, March.