SWPTC

SWEDISH WIND POWER TECHNOLOGY CENTRE

Final Report

2010 - 2014

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Project title	Swedish Wind Power Technology Centre
Project number	Swedish Energy Agency; P-nr: 32591-1, Dnr:2009-003525
Organisation	Chalmers University of Technology, Dept. of Energy and Environment
Chairman of the board	Matthias Rapp
Project leader	Ola Carlson
Project coordinator	Sara Fogelström
Other participants	Six Theme group leaders:
	Ola Carlson, Division of Electric Power Engineering, Dept. of Energy and Environment, Chalmers
	Lars Davison, Division of Fluid Dynamics, Dept. of Applied Mechanics, Chalmers
	Viktor Berbyuk, Division of Dynamics, Dept. of Applied Mechanics, Chalmers
	Thomas Abrahamsson, Division of Dynamics, Dept. of Applied Mechanics, Chalmers
	Lina Bertling-Tjernberg, Division of Electric Power Engineering, Dept. of Energy and Environment, Chalmers (2010 - August 2013) /
	Michael Patriksson, Division of Mathematics, Dept. of Mathematical Sciences, Chalmers (July 2014 – September 2014)
	Jan-Olof Aidanpää, Mechanics of Solid Materials/ Product and Production Development, Department of Engineering Sciences and Mathematics, Luleå Technical University
Report for	2009-11-10 – 2014-09-30
Academic partners	Luleå University of Technology, Swerea, Chalmers University of Technology
Industrial partners	ABB, DIAB, DNV, GE Wind Energy, Göteborg Energi, Marström Composite, Semcon, SKF, Triventus Service/Connected Wind Services, Vindmark Technologies, WindVector

Project description

The aim of the Swedish Wind Power Technology Centre, SWPTC, is to support Swedish industry with knowledge of wind turbine design and components thereof. The main goal is to reduce the cost of design, construction and maintenance of wind turbines and ultimately to reduce the cost of electric power to consumers.

The Centre has concentrated on wind turbines with an output of more than 2 MW, suitable for positioning in open countryside, in forests, in cold climate or offshore. Together with six companies interested in wind power technology, Chalmers started the Swedish Wind Power Technology Centre (Svenskt VindkraftsTekniskt Centrum) in 2010. During 2011 three more companies joined the Centre and during 2012 five more partners, both industrial and academic, joined the Centre. At the end of 2013 two members, GE and Semcon, choose not to extend their membership in SWPTC. During 2014 the number of industry partners was nine and the academic partners were three.

The SWPTC has organised its work in six theme groups.

- Power and Control Systems
- Turbine and Wind Load
- Mechanical Power Transmission and System Optimization
- Structure and Foundation
- Maintenance and Reliability
- Cold Climate

The research was carried out in project form in close cooperation with industry, some for detailed research efforts for deep knowledge as well as broader ones that cover several themes. The large projects focused on a complete design which takes the interaction between all components into account to design an optimal wind turbine.

At Chalmers there were six divisions active in the SWPTC projects; Electric Power Engineering, Automatic Control, Automation and Mechatronics, Dynamics, Fluid Dynamics, High Voltage Engineering and Mathematics. Mechanics of Solid Materials and Product and Production Development at Luleå Technical University and Swerea Sicomp, Swerea IVF and Swerea Kimab also work within the Centre. The Centre was unique in the way that many divisions cooperate in one Centre.

Results

During stage 1, the Centre had 15 projects on-going. The Centre employed eight PhD-students and 15 senior researchers. As supervisors, on part time basis, around ten permanent employees at Chalmers have been engaged, mainly at professor or associate professor levels. Around 30 people from the member companies also worked with SWPTC projects. In total the Centre generated 26 man-years of work.

The project portfolio was covering the subjects of the six different theme groups. This indicates that the projects had a broad content and covered the most important parts of a wind turbine design.

Several Master of Science courses at Chalmers have during the years been developed and carried out teaching in wind power as specific assignments in more general courses with electrical, mechanical as well as mathematical content.

Personnel from SWPTC contributed to an annual external wind power course, offered via Chalmers Professional Education. The course covered development of wind farms, finance, electric power engineering, control, dynamics and fluid dynamics.

The Centre has developed theories and simulation models of wind turbines or parts of the wind turbine. Some projects have developed highly detailed theoretical models, other projects have built up laboratory models in order to validate simulations, and some projects have had the opportunity to test their models against full scale equipment. Several member companies and project partners have delivered and/or given access to equipment that have been used within the Centre. The Centre had access to Big Glenn (a 4 MW turbine in Gothenburg's harbour) and the adjoining HVDC facility, made tests at Chalmers' small wind turbine at Hönö, received SCADA data for several large turbines, made measurements in cold climate lab in Luleå and Chalmers, also made measurement in a wind tunnel, built up laboratory test objects of the electrical and mechanical drivetrain of a wind turbine, received thermal measurements from a wind farm in cold climate, as well as made test in Swerea's labs.

For an overview of the results see the reports from the theme group. The detailed results are described in respective project report.

The main results from stage 1 are:

- A stochastic model for predictive turbine control strategies based on upwind velocity and direction measurements and load measurements was developed. These strategies allow (1) mitigation of turbine loads at high wind speeds; (2) more precise regulation close to limits that has the additional potential of improving turbine efficiency at high wind speeds
- A method for detecting electrical faults in the generator
- Developed a system for a complete grid code testing of wind turbines.
- A LIDAR to measure the speed of wind has been designed, constructed and, eventually mounted on the Big Glenn.
- Three different prescribed wake approaches (lifting line, lifting surface, panel method) of steady vortex method application for wind turbine's aerodynamic loads have been developed. Further, a time-marching vortex lattice free wake (VLFW) has been developed which can be used to predict the wind turbine aerodynamic loads for different operating conditions such as turbulent inflow and yaw condition.
- A method for simulating atmospheric boundary layers under the direct influence of a forest has been implemented in an in-house CFD (Computational fluid dynamics) code. The implementation includes the effect of the Earth's rotation (Coriolis effect), the possibility to simulate various

stability classes of the ABL (surface heating/cooling -> unstable/stable ABL) and the forest model itself.

- A model to study torsional drive train vibration dynamics of a generic indirect drive multi-MW wind turbine has been developed. The main focus lies on developing a fully parameterized computational model of a multi-stage gearbox which fulfils the requirement of a proper gear dynamic representation appropriate for multibody formalism as well as the requirement to be computationally efficient. The models are targeted to the developed physical test rig of scaled down drive train. The models and the test rig are used to study vibration dynamics, system misalignments and how the misalignments affect the internal dynamics of drive train functional components (bearings, shaft couplings, others) for different load cases, e.g. emergency shutdown.
- A method to estimate the risk of failure in a wind turbine bearing after 20 years of service under varying wind conditions was developed. It was found that a quasi-static model is sufficient for estimating the bearing life of main support bearings in the no gearbox concept, but not for the bearings carrying the generator stator.
- A system simulation tool called FreeDyn has been developed. As it is a huge difficulty to build wind turbine simulation tools as they quickly become overwhelming in the very different competences needed (aerodynamics, solid mechanics, control, electronics) the main aim of FreeDyn is to define a good interface between different component models (blade, tower, nacelle, control unit etc.).
- A new bearing concept with a low-cost base material and a high performance raceway produced by Hot Isostatic pressing (HIP) has been developed. Several promising materials combinations have been identified.
- Model reduction techniques designed to allow more direct coupling between high-quality blade models and reduced-order models for aeroelastic simulations have been developed.
- A finite element based study of composite wind turbine blade modelling has been made as well as an investigation of methods for wind turbine system modelling. A detailed model of the NREL 5MW virtual test bed wind turbine blade has been developed.
- A artificial neural network-based condition monitoring methodology was created; it uses the measurements stored in SCADA along with the SCADA alarms and warnings to estimate the health of the components being monitored. The system was able to detect a fault in the gearbox bearing in advance, providing an opportunity to plan the replacement activity.
- A computer code for analyses of bearing current activity under alternating voltages has been developed. Bearing capacitance has been calculated, the electrical breakdown of the rotating bearing has been characterised as well as the lubricants in bearings has been electrically characterised.
- A demonstrator for the ice detection system based on controlled acoustic waves, magnetostrictive actuator and accelerometers was developed along with another demonstrator for the laser based sensor for ice detection. An experimental set-up with the demonstrator in cold climate lab (CCL), composite test object and equipment for glaze and rime ice production have been developed. Both ice detections systems shows promising results for early detection of ice and water.
- Experimental techniques for evaluating deicing systems have been developed. Also tools for simulating the deicing process have been developed. Test laminates was manufactured and modelling of degradation of material due to heat has been developed.

Finances

During the four years, the Centre has received 51 289 333 SEK in gross revenue, whereof 65 % comes from the Swedish Energy Agency, 17 % comes from member companies and project partners and 18 % from the Academic partners. The total cash budget for SWPTC was 50 million SEK.

82 % of the received funding has gone to approved projects. The remaining sum has financed the Centre management as well as the research management done by the theme group leaders.

During stage 1, all in-kind work has been carried out. The industrial companies have carried out 120 % of their share, and the academic partners have carried out 172 % of their share.

For more details about the Centre's finances see the attached final financial report.

Other internal activities

Every year in May, SWPTC hosted an internal conference where Board members and industry representatives could meet the PhD-students and researchers. During the conference all projects were presented and discussed.

During stage 1 SWPTC has had 19 Board meetings and seven Partner meetings.

Deviations from project plan

The Centre was extended for an extra year during 2014 due to a slow start in 2010. There were no extra funding for 2014, but the extension gave the projects time to better fulfil their goals. The project ended at 2014-09-30.

Publications

The Centre has published seven journal papers and 27 conference papers during stage 1. Eleven more paper has been submitted for conferences and journals during this period. Two reports have also been written during stage 1. Four Licentiate theses have been presented during this time.

Eleven Master theses have been carried out in cooperation with SWPTC-projects during stage 1.

External activities

Together with Vindforsk and Vindval, and the Swedish Energy Agency, SWPTC has arranged the research conference *Wind Power Research in Focus* three times (24-25 November 2010, 18-19 January 2012 and 16-17 September 2013) during stage 1. At the conferences all SWPTC-projects were presented with posters. Some of the projects also gave oral presentations at the conferences. The average number of participants was 200.

During stage 1 SWPTC has initiated work on realising a test station for wind turbines in cold climate. The work has been going on during the whole stage. At the beginning the project was managed by a steering committee governed by SWPTC, administrated by Chalmers Industriteknik and executed by Scandinavian Wind AB. By the end of June 2013 the continuation of the project were taken over by SWEREA Mefos. The goal is to build a test centre for cold climate testing of wind turbines and wind turbine components. The test centre would also provide the academic and industrial researchers with a test facility for wind power research activities in cold climate conditions.

At three occasions during stage 1 SWPTC has been involved in a wind power course for companies. The course included basic knowledge about development and turbine technology.

SWPTC applied and was granted membership in EWEA in September 2013. During stage 1 the Centre applied for associated membership in EEWA and is waiting for reply. Ola Carlson, director of SWPTC, became a member of TP Wind during stage 1.

Theme group	Power and Control Systems
Theme group number	1
Theme group leader	Ola Carlson
Organisation	Chalmers University of Technology, Electric Power Engineering
Participants	Chalmers, ABB, Göteborg Energi, GE, WindVector
Report for	2009-11-10 – 2014-09-30

Theme group description

Within the theme group Power and Control Systems the work covered the electrical generation system and control of the wind turbine. The research dealt with development of methods for fault detection in generators, grid code testing and control to reduce the loads in the wind turbine. Practical experience was an important part of this applied wind energy research and measurements from wind turbines and laboratory setups were valuable for understanding the behaviour of the wind turbine and for model validation.

Results

Several electrical drive train models of a wind turbine with a direct driven generator and full power frequency converter have been developed. A standard model for dynamic and transient operation of a wind turbine has shown good agreements with measurements from the wind turbine GE4.1/113, Big Glenn. Power, speed, torque, current and voltage quantities agreed well in comparison between the model and the operation of the wind turbine. This type of model, or simplified ones, are suitable to be used when the simulations of the complete wind turbine, electrical and mechanical parts, is carried out. One main focus of the research has been on generator models for faulty operation and methods of detecting faults in the generator. As turn-to-turn faults in the generator is one of the more common reasons of generator failure it was chosen as the failure to model. A method to analyse and detect minor faults in the generator has been developed with promising results. Laboratory test are on the way.

The power electronic converters in one project has been the standard AC/DC/AC converter, they have been modelled for operation in normal conditions in the wind turbine and as controllable voltage source converters to emulate the voltages dips accordingly to the Grid Codes. It has been shown, by simulations and laboratory tests, that the converters are most suitable to be used as a controllable voltage source when preforming Grid Code-testing of wind turbines. Four special made converters have been designed, set in operation and used in the laboratory for the grid code tests. Göteborg Energi have supported the Centre by installing two 8 MW HVDC-light converter stations close to the wind turbine, Big Glenn. This will make it possible to test the Grid Codes for wind turbines in full scale. The status of the installation is that all equipment is in place and all tests before connecting the wind turbine has been carried out with success. First grid code test is planned in the beginning of December 2014.

A scaled down laboratory test rig of high-speed shaft subsystem of drive train of a wind turbine has been developed. ABB® has provided a considerable amount of equipment as in-kind contribution to the test rig development. It consist of a pair of 400 V, 3 phase, and 6 pole induction motors with frequency converters capable of delivering shaft rotational speeds up to 1500 rpm. The test rig has been instrumented by SKF WindCon system (Multilog system with corresponding software package (SKF @ptitude Observer®). The unique part of the test rig is the instrumented bearing housing. It was designed with springs, whose deformation can be used to calculate the forces acting on the bearings.

With respect to control of wind turbines there has also been significant development to reduce loads in the wind turbine, and this was achieved through full control of generator shaft torque via the electrical system and by controlling blade pitch angle to reduce loads on the blades. Measurements data from the wind turbine GE 4.1/113 have been used to validate the models used to develop the control actions in the wind turbine. To support the load reduction, a LIDAR measurement system has been developed. The LIDAR has also been set in operation on top of the nacelle of the wind turbine Big Glenn. Wind speed measurements have been carried out and comparison has been done with the wind sensor on the nacelle and the power production of the wind turbine. There is a need of more measurements to be able to make a proper evaluation of the LIDAR system.

One licentiate thesis, six journal papers and ten conference papers have been published and one journal paper has been submitted for the 3rd time. Four master theses work have also been conducted.

Theme group	Turbine and Wind Load
Theme group number	2
Theme group leader	Lars Davidson
Organisation	Chalmers University of Technology, Applied Mechanics, Fluid Dynamics
Participants	Chalmers, GE, WindVector, DIAB, Vattenfall, SKF, DTU Wind Energy, Teknikgruppen
Report for	2009-11-10 – 2014-09-30

Theme group description
This research was focused on aerodynamics loads on rotor blades. The theme group included two research projects, TG2-1 *Turbine and Wind Load* (PhD student Hamid Abedi) and TG2-2 *Fatigue loads in forest regions* **(**Bastian Nebenführ).

Results
TG2-1 Aerodynamic loads on rotor blades
The aim of the project was to develop computational methods for predicting unsteady aerodynamic loads on wind turbine rotor blades. The focus of the project was to handle transient loads by the Vortex Method in which tabulated lift and drag coefficients are used.

The three different prescribed wake approaches (lifting line, lifting surface, panel method) of steady vortex method application for wind turbine's aerodynamic loads have been developed. Further, a time-marching vortex lattice free wake has been developed which can be used to predict the wind turbine aerodynamic loads for different operating conditions such as turbulent inflow and yaw condition.

The implemented vortex method has been validated by comparison with the Blade Element Momentum (BEM) method, the GENUVP code by National Technical University of Athens (NTUA), Hönö turbine measurement data and MEXICO wind tunnel measurements.

There was a cooperation with the project "Hönö turbine properties and thrust vector at yaw misalignment" (financed by Energimyndigheten), where the power generation and thrust vector at significant yaw misalignment was studied (see Publications section). The results were compared with the experimental data provided by Scandinavian Wind AB.

TG2-2 Fatigue Loads in Forest Regions
A method for simulating atmospheric boundary layers under the direct influence of a forest has been implemented in an in-house CFD (computational fluid dynamics) code. The implementation included the effect of the Earth’s rotation (Coriolis effect), the possibility to simulate various stability classes of the ABL (surface heating/cooling → unstable/stable ABL) and the forest model itself. The forest was modelled as an increased drag force on the flow, similar to a porous medium.

One major concern was to simulate the atmospheric boundary layer over the forest for different thermal stratifications (that can be interpreted as simplified weather conditions). A study has been carried out simulating six different regimes of thermal stratification, ranging from unstable to very stable conditions. The different regimes were identified from the available field measurement data at Ryningsnäs. The influence of two different sub-grid scale models on the results was studied.

During an extended visit to Northeastern University in Boston (April – July, 2013), a reduced order model of the NREL 5MW standard wind turbine was developed. Using this model and ViDyn, fatigue loads for the NREL standard wind turbine were calculated based on two LES: one with and one without a forest. It was shown that the IEC design criteria were largely exceeded and the tower base bending moment was increased in the forest case.

Theme group	Mechanical power transmission and system optimisation
Theme group number	3
Theme group leader	Viktor Berbyuk
Organisation	Chalmers University of Technology, Electric Power Engineering
Participants	Chalmers, ABB, SKF, GE, Semcon
Report for	2009-11-10 – 2014-09-30

Theme group description

The research within the following areas was in focus in Theme Group 3 (TG3):

- Advanced engineering analysis of dynamics of power transmission systems in wind turbines
- Drive train system modelling, model validation and accelerated testing
- Vibration dynamics and vibration control in multi-MW wind turbines
- Development of Compound Bearing Concept
- System simulation and multi-criteria optimisation for robust and cost-effective design of multi-MW wind turbines.

Results

The Theme Group 3 work has been directed to preparation of the project applications, coordination of the research within the group focus areas, support for the presentation of the obtained results on national and international seminars and conferences. The following projects have been initiated and coordinated during the reporting period: TG3-1 *Wind turbine drive train dynamics, system simulation and accelerated testing* (project leader Viktor Berbyuk), TG3-2 *Development of compound bearing concept for wind power applications* (project leader Sven Haglund), TG1-5 *Measuring of a wind turbine for verification of component design* (joint project together with the Theme Group 1, project leader Ola Carlson), TG6-1 *Sensors for Ice Detection on Wind Turbine Rotor Blades* (joint project with Theme Group 6, project leader Viktor Berbyuk).

Reporting of the project status, coordination and planning of the future research, application of the results obtained as well as their use in engineering education (MSc project, BSc project, teaching of master courses) have been in focus on regular TG3 meetings (3-4 meetings per year). It was customary to organize the TG3 meetings both at Chalmers as well as in our industrial partners (SKF, ABB, Semcon).

Here are some particular results obtained within the projects of the theme group.
The review of the state-of-the-art on modelling and simulation of wind turbine drive train system dynamics has been done and was published. The mathematical and computation models have been developed to determine and analyse the torsional and flexural vibrations in high-speed shaft subsystem of a wind turbine drive train. The models were targeted to the developed physical test rig of scaled down drive train (more details about the test rig available in the report on TG1-5 project and in publications, see project report). The models and the test rig were used to study vibration dynamics, system misalignments and how the misalignments affect the internal dynamics of drive train functional components (bearings, shaft couplings, others) for different load cases, e.g. emergency shutdown. Validation of mathematical models of drive train and its components has been also in focus. Some results of computer simulations of vibration dynamics of high-speed shaft subsystem of drive train has published.

The investigation on how the chosen level of detail in the drive train model affects measures for fatigue life of main and rear bearing of direct drive wind turbine has been performed. The obtained results were presented on EWEA2014 Conference. As a model problem for accelerated testing, the effect of misalignments on the fatigue life of disc couplings was investigated. Several experiments have been carried out to determine parameters of shaft coupling obtained from SKF.

Within the system simulation task of the project, the wind conditions module has been created. It is based on the existing tool SOSIS-W. The original Fortran 77 standard code was re-formulated into Fortran90/95 standard. Besides the modelling itself, the optimisation tool has also been selected. The DAKOTA (Design Analysis Kit for Optimization and Terascale Applications) is an open-source code developed by Sandia National Laboratories and it is capable of design of experiment study, optimisation, etc. The work was continued on the system integration tool FreeDyn. As it is developed so far the current version includes base-models for all components of a wind turbine. Due to that the generator model does not allow for proper modelling of electrical phenomena which is required to fully investigate the mechanical effects of different kinds of electrical faults (e.g. grid loss, short-circuit in one electrical phase) this issue was in focus. Developing of the extended current generator model is ongoing and is expected to be finalised at the end of 2014 within the approved extension of the FreDyn project.

There were a number of interesting materials that potentially could be used as high strength bearing materials. They were however very expensive. One possibility to take advantage of these materials anyhow was to use them only where needed, i.e. in the raceway of the bearing. One of the basic ideas has been studied how to design a compound bearing with a base in cheaper material, preferably cast that is coated with a raceway in high strength material. The method has been suggested of making the compound bearing through a powder metallurgical route, where the cast base is put in a capsule and raceway material is Hot Isostatic Pressed (HIP) onto the base material. This gave a fully dense material and a good adhesion between base and raceway. To manufacture bearings in this way gave the opportunity to tailor the properties of the bearing. Three different candidates for the raceway material were chosen: one tool steel, one stainless steel and one high speed steel. All three steels had Ms-temperatures around 200°C. The tool steel required a high temperature tempering and the two other steels required a low temperature tempering. Powders of all three alloys have been manufactured. For the core material nine candidate materials were chosen for the simulations. The materials were chosen to cover a large range of different properties: a range of Ms-temperatures from 200°C to 400°C, mild to very good hardenability and low to high carbon content. A simulation with cast iron as core material was also performed.

More details about the results obtained within the projects TG3-1, TG3-2, TG1-5 and TG6-1 are available via the project reports.

The results of the research activity within the Theme Group 3 have been published in one journal paper, one textbook “Structural Dynamics Control” (Second Edition, Chalmers 2014), four conference papers, six MSc thesis reports, and one BSc thesis report.

Theme group	Structure and foundation
Theme group number	4
Theme group leader	Thomas Abrahamsson
Organisation	Chalmers University of Technology, Applied Mechanics
Participants	Chalmers, GE Wind Energy, DIAB, Marström Composite
Report for	2009-11-10 – 2014-09-30

Theme group description

Theme group 4 focused on solid mechanics issues (as opposed to fluid mechanics issues) that related to the wind turbine load carrying structure, including its foundation. The original ideas that formed the work of theme group 4 were as follows:

- To verify that methods for load identification can be used for loads on wind turbines and to develop these further
- To test methods for calibration and updating of simulation models of wind turbines and to draw conclusions for future modelling
- To test alternative methods for the monitoring of the health status of the wind turbine
- To attempt to examine potential savings by using probabilistic structural sizing methods

Of these bullets, the vast majority of work has been focused on methods for calibration (and validation) of models and methods for structural sizing.

Results

Most of the work made within the area of theme group 4 has been conducted in one PhD student project called TG4-1 and one post-doctoral project called TG4-2.

In TG4-1 *Validation of Wind Turbine Structural Dynamics Models* a strong focus has been put on the development of model reduction and model validation methods. The work has been made in preparation for an (initially planned) large scale calibration following vibrational testing of blades for an off-shore wind turbine. The test did not materialise, because of the shift of focus at GE Wind as a reaction to disappearing business opportunities in the volatile off-shore wind turbine market. That shift of focus appeared very early during the project. However, the method development has been advancing and is now in a good position for real large scale calibration and validation. The work has resulted in three papers related to model reduction, two papers related to calibration/validation and two papers on modelling/simulation. In addition to the above listed publications, a couple of publications have been produced as in-kind contribution to TG4-1 from Chalmers/Applied Mechanics.

In TG4-2 *Evaluation of manufacturing methods and material selection for cost optimal rotor blades* a study of composite wind turbine blade modelling using the finite element method in collaboration with CCG, Composites Consulting Group. An investigation of methods for wind turbine system modelling has been made with the support of Teknikgruppen AB. A detailed model of the NREL 5MW virtual test bed wind turbine blade has been developed in collaboration with CCG Composites and the parallel project TG4-1. Model reduction techniques designed to allow more direct coupling between high-quality blade models and reduced-order models for aeroelastic simulations have been investigated in collaboration with the sister project TG4-1. Synergy has been obtained from a parallel project (involving the project partner Marström Composites and the consultancy company Scandinavian Wind) that aims at developing and install new blades for Chalmers experimental wind turbine at Hönö. The manufacturing of the new blades to the Hönö 50kW machine has recently started. A measurement series will commence shortly. Studies of the Brazier effect, a nonlinear effect which causes conservative material selection for the core material towards the root section of many commercial blades, have been performed together with CCG Composites. This work consisted partly of simulation work using the NREL model previously developed in the project and partly of experiments on representative scale models tested at DIAB's laboratory in Laholm. The above activities are aimed to support the development of an optimisation tool for wind turbine system design. The work of TG4-2 has been reported in four papers and two reports. In addition to the above listed publications, a couple of publications have been produced as in-kind contribution to TG4-2 from Chalmers/Applied Mechanics.

Theme group	Maintenance and Reliability
Theme group number	5
Theme group leader	Lina Bertling Tjernberg (up to 130831) / Michael Patriksson (from 140701)
Organisation	Chalmers University of Technology, Electric Power Engineering
Participants	Chalmers, ABB, Göteborg Energi, Triventus Service
Report for	2009-11-10 – 2014-09-30

Theme group description

The theme group mainly concerned the work of two PhD students at Chalmers: Joshi Abhishek (since 2011) at High voltage engineering, Department of Materials and Manufacturing Technology, and Pramod Bangalore (since 2011) at Department of Electric Power Engineering. Focus lay on the reliability and maintenance of wind turbine components.

The work of Joshi Abhishek mainly concerned the study of phenomena occurring in the bearing when exposed to shaft voltages. The work involved an experimental investigation and characterization of the current flowing through a bearing, when exposed to a shaft voltage, and an elucidation of the responsible mechanisms, electrical characterizations of different commercially available lubricants, the establishment of a model describing the phenomena occurring in a bearing that could be implemented in the following system analysis, and an overview inventory of bearing failures due to suspected bearing currents.

The work of Pramod Bangalore aimed to increase the availability of wind turbines, while reducing the overall costs of their maintenance. The work utilised the abundant data available from the SCADA system of the wind turbine, in order to estimate the state of critical components, and to make a focused maintenance effort on those components that are at a risk of failure.

Results

The work of Joshi Abhishek and his supervisors contributed to the fulfilment of several of the Centre's goal. A better understanding of bearing currents, their detrimental effect – and thus how they can be mitigated – will reduce the costs for exchanging damaged bearings, and thus contribute to a longer lifetime of the turbine. When increasing power electronic components in the system in order to reduce weight it is important to consider effects on bearing currents. The project also contributes to research of the highest class through a state-of-the-art study of fundamental aspects of a mechanical bearing considered as an electrical component as a part of an electrical circuit. In addition, it also contribute to the engineering education since these phenomena is relevant to use as application examples in the subject of high voltage engineering.

The work of Pramod Bangalore and his supervisors has led to the creation of a maintenance management framework, referred to as SEMS (Self-Evolving Maintenance Scheduler). The SEMS framework – which is based on the data stored in the existing SCADA system of the wind turbine – adapts this data in order to estimate the health of critical components. An artificial neural network model incorporates the indication of failures from various CMS systems, and was used to produce signals indicating anomalous operations. A maintenance management framework was also proposed, in which a mathematical optimisation model – developed in cooperation with Mathematical Sciences – may indicate also additional, opportunistic, maintenance possibilities on other components in order to optimise the overall maintenance cost.

Theme group	Cold Climate
Theme group number	6
Theme group leader	Jan-Olov Aidanpää
Organisation	Luleå University of Technology, Mechanics of Solid Materials
Participants	LTU, Swerea, Chalmers, Vattenfall AB, Skellefteå Kraft, DNV KEMA, H Gedda Consulting, Bollebygds Plast, DIAB, SKF; WindVector
Report for	2009-11-10 – 2014-09-30

Theme group description

In Sweden we have today an increase of wind power projects in regions with cold climate. Even if at least 20 GW of wind power has been installed internationally in cold regions the knowledge is based on experience more than scientific evidence. Until now the main focus for cold climate research has been on prediction, detection and de-icing equipment's. Cold climate and icing can cause production losses and reduction of life time for the wind power units and it is therefore essential to get more insight in how to operate the machines in cold climate.

The following areas of interest have been located:

- Development of ice detection equipment's
- Development of de-icing equipment's
- How to operate a wind power unit in cold climate
- Modelling of icing and de-icing
- Dynamic modelling to evaluate loads due to icing
- Fatigue and fracture mechanics due to cold climate

The aim for theme group 6 is to:

- Develop and evaluate technology for ice detection and de-icing.
- Develop tools and technology for cost effective operation in cold climate
- Optimization of operation in cold climate
- Development of tools for simulation of icing and de-icing
- Development of design methods to avoid fatigue and fracture in wind turbines
- Develop tools for analysis of tribology in cold climate
- Support the development of a test site for wind power in cold climate

Results

The 6th theme group was initiated during autumn 2012 and therefore only two projects have been initiated, TG6-1 *Sensors for Ice Detection on Wind Turbine Rotor Blades* and TG6-2 *Efficiency and influence of heating device on wind turbine blades*. Both projects will be finished during 2014.

TG6-1 Sensors for Ice Detection on Wind Turbine Rotor Blades

The project provided a demonstrator for the ice detection system based on controlled acoustic waves, magnetostrictive actuator and accelerometers. An experimental set-up with the demonstrator in cold climate chamber, composite test object and equipment for glaze and rime ice production has been developed.

The obtained results show that the formation of ice, the ice mass, icing areas and the temperature have a significant influence on guided wave propagation w.r.t. Fourier transform, amplitude attenuation and RMS values as indicators. It was also shown that there is no significant damping in the material that has been tested concluding that the proposed ice detection system based on controlled acoustic waves is a promising approach for ice detection.

TG6-2 Efficiency and influence of heating device on wind turbine blades

In the project there was an aim to get thermal measurements on a real wind turbine during the deicing process. A test procedure by using a mini helicopter with thermal camera was developed and in September 2014 a first successful test was performed. The test will be used to evaluate the developed models for deicing in the project. Several test plates have been manufactured at Swerea Sicomp with a lay-up and heating system similar to the ones used in wind turbines. These plates were then used for de-icing tests in a cold climate room at LTU. Simulation models and experimental methods were developed to study the deicing process.

New techniques for de-icing have also been studied in the project by Bollebygds Plast and student projects. Bollebygds Plast manufactured similar plates with excellent thermal properties. Bollebygds Plast also assisted in the development of the test plates to get better thermal properties. Student projects have studied inflatable rubber on the leading edge to break the ice and ice-phobic coating. However, none of these methods were concluded to be suitable for wind turbines. Today an ongoing student project studies where piezoelectric plates are going to be used to create high frequency waves to separate ice from the blade.

Studies of the degradation due to heated laminates have been performed at Sicomp. Several details of the blade were studied in the simulations. The conclusion from these studies was that degradation should not be a problem if the system works properly.

Project title	Stochastic Model Predictive Control of Wind Turbines: Extension
Project number	TG1-1
Organisation	Chalmers University of Technology, Signals and Systems
Project leader	Professor Bo Egardt
Other participants	Alexander Stotsky (Researcher)
Report for	2011-01-01 – 2013-10-30
Participating companies	ABB, Göteborg Energi, GE, WindVector

Project description

New stochastic model predictive turbine control strategies based on upwind velocity and direction measurements and load measurements were developed within the project TG1-1 *Stochastic Model Predictive Control of Wind Turbines.* These strategies allow (1) mitigation of turbine loads at high wind speeds; (2) more precise regulation close to limits that has the additional potential of improving turbine efficiency at high wind speeds.

Results

The results show potential load reduction and turbine power output improvement due to availability of the wind speed preview information, provided by the laser wind speed measurement system (LIDAR). Look-ahead calculations, constraints on blade loads, robust drivetrain controllers, improvements of the pitch transients as well as post-processing techniques for estimation of the turbine parameters were key elements of the new proactive control concepts developed within this project. A new turbine model validation technique that was based on adaptation of look-up tables was also developed. Simulation results from the VIDYN turbine simulation program and measurements from Big Glenn wind turbine, located outside Gothenburg were used as an input to this new model validation technique. The models of the flapwise bending moment and power coefficient were validated for Big Glenn turbine. Measurement data were acquired during normal turbine operation. Verification results showed good agreement between model outputs and measured data. The method allowed prediction in a wide range of turbine operating variables, using only few measured points. Validated models were simple enough to be used for control design and simulations.

Six journal papers have been published within this project [1] - [6]. Four papers were presented on the reputable IFAC and IEEE conferences [7] - [10].

Fulfilment of SWPTC's goals

The project contributes to the following SWPTC goals:

- General build-up of a turbine modelling know-how that will eventually facilitate high-quality training of engineers in wind power area
- High-class research aimed at achieving optimal operation of wind turbines
- Increase of the turbine life time due to better load and power modelling and predictions
- Publications in respected international scientific journals and presentations at reputable international conferences

Deviations from project plan

The deviations from the project plan were minor.

Publications

Journal Papers

1. A. Stotsky, *Wind Turbine Model Validation: Fusion of Simulation and Measurement Data*, Proc. IMechE Part I: Journal of Systems and Control Engineering, vol. 228, N 9, 2014, pp. 734-737.
2. A. Stotsky, B. Egardt, O. Carlson, *An Overview of Proactive Wind Turbine Control*, Energy Science and Engineering, N 1, 2013, pp. 1-10.

3. A. Stotsky, B. Egardt, *Data-Driven Estimation of the Inertia Moment of Wind Turbines: A New Ice Detection Algorithm*, Proc. IMechE Part I: Journal of Systems and Control Engineering, vol. 227, N 6, 2013, pp. 552-555
4. A. Stotsky, B. Egardt, *Individual Pitch Control of Wind Turbines*: Model-Based Approach, Proc. IMechE Part I: Journal of Systems and Control Engineering, vol. 227, N 7, 2013, pp. 602-609.
5. A. Stotsky, B. Egardt, *Model Based Control of Wind Turbines: Look-Ahead Approach*, Proc. IMechE Part I: Journal of Systems and Control Engineering, vol. 226, N 8, 2012, pp. 1029-1038.
6. A. Stotsky, B. Egardt, *Proactive Control of Wind Turbine with Blade Load Constraints*, Proc. IMechE Part I: Journal of Systems and Control Engineering, vol. 226, N 7, 2012, pp. 985-993.

Conference Papers

7. A. Stotsky, *Wind Turbine Model Validation: Fusion of Simulation and Measurement Data*, 19-th IFAC Congress, Cape town, South Africa, August 22-29, 2014, pp. 3629-3632.
8. A. Stotsky, B. Egardt, O. Carlson, *Control of Wind Turbines: A Tutorial on Proactive Perspectives*, 2013 American Control Conference (ACC), Washington DC, USA, June 17-19, 2013, pp. 3435-3442.
9. A. Stotsky, B. Egardt, *Robust Proactive Control of Wind Turbines with Reduced Blade Pitch Actuation*, IFAC Multi-Conference on Systems Structure and Control, Grenoble, France, February 4-6, 2013, pp. 690-695.
10. A. Stotsky, B. Egardt, *Model Based Control of Wind Turbines: Look-Ahead Approach*, 7-th IFAC Symposium on Robust Control Design, Aalborg, Denmark, June 20-22, 2012, pp. 639-646.

External activities

- Stotsky participated and presented a paper at the 19-th IFAC Congress, Cape town, South Africa, August 22-29, 2014.
- A. Stotsky participated and presented a paper at the 2013 American Control Conference (ACC) in Washington DC, USA, June 17-19, 2013.
- Stotsky participated and presented a paper at the IFAC Multi-Conference on Systems Structure and Control, Grenoble, France, February 4-6, 2013.
- Stotsky participated at the conferences “Vindkraftforskning i fokus” at Chalmers, and contributed with posters and a presentations (2012, 2013).
- Stotsky organized and participated in the VIDYN training course given by
- Teknikgruppen and Scandinavian Wind AB (February – June, 2013). The training was successful and attracted a number of participants from Mechanical and Control Engineering Departments. The participants gained a valuable practical experience, when using VIDYN for turbine simulations. In addition, advantages and limitations of VIDYN simulation platform were identified and discussed openly in this training course.
- Dr. David Schlipf from the University of Stuttgart, Germany visited the Control Engineering Department and SWPTC and gave a talk on LIDAR-enabled wind turbine control (September 2013).
- Professor Rafal Wisnievski from the University of Aalborg, Denmark visited the Control Engineering Department and SWPTC and gave a talk on proactive wind turbine control (September 2012).
- Stotsky participated and presented a paper at the7-th IFAC Symposium on Robust Control Design, Aalborg, Denmark, June 20-22, 2012.

Project title	Models of electrical drives for wind turbines
Project number	TG1-2
Organisation	Chalmers University of Technology, Electric Power Engineering
Project leader	Ola Carlson
Other participants	Joachim Härsjö (PhD student)
Report for	201-03-01 - 2014-09-30
Participating companies	ABB, Göteborg Energi, GE

Project description
The aim of this project was to develop sufficiently accurate and suitable models of the electric drive system to be integrated into the mechanical system of a wind turbine. There are several different drive system used today, this project mainly focused on the development and adaption of a model of the full power converter used with a direct drive generator. The direct drive generator modelled in this project was a permanent magnet synchronous machine, as the one used in the Big Glenn wind turbine in Gothenburg. Model validation using measurements from a 4 MW wind turbine was performed as a part of this project. One of the tasks of this project was to develop models of the generator and the power electronic converters and to use the developed models to analyse the wind turbines response to dynamic/transient within the electrical grid. The drive train was modelled through analytical equations, where the generator was modelled using the state-space representation due to its more general nature. This type of representation was chosen as it could be easily shared and be used in other projects within SWPTC.

A different part of this project was to develop diagnostics methods by using the models developed in the first part of the project. The aim was to use the models to identify deviations from normal behaviour and depending on the nature of the deviation, conclusions can be deducted on which component has failed.

A minor literature study on future possibilities for both generators and power electronics was also conducted. This was in order to see the possible effect it poses on wind turbines when it comes to cost, weight and efficiency.

Results
A complete analytical system model was created; consisting of a simplified mechanical drive-train, generator model, a converter with corresponding generator controller, DC-link with overvoltage protection, a grid side converter with corresponding filter and controller and a grid synchronisation method (a phase locked loop), see Figure 1.

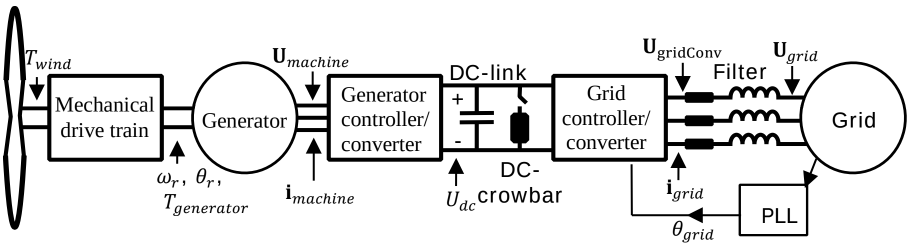


Figure 1: An overview of the modelled system together with the measured quantities.

The system was built using sub-modules in order to make it more flexible to easily be able to change/alter individual parts of the system. All the sub systems have been simulated individually to verify a correct behaviour before connecting them in to the complete system. Once all sub systems were verified a complete simulation was performed with satisfying results. The simulated results were compared to measurements from the 4.1 MW wind turbine, Big Glenn, and the results was agreeing well, see Figure 2. There was a small error between the measurement and simulations as the converter losses are not accurately modelled as this was out of scope for this project.

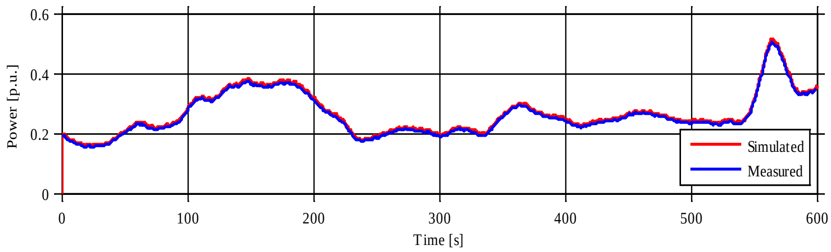


Figure 2: Simulated and measured power delivered to the grid

For the diagnostics part, a method (presented in one of the research paper) which could detect both mechanical and generator faults was implemented. The method utilised that larger direct drive generators has several sets of stator windings in parallel. The method was made to work during sensorless conditions in order to be more reliable. This method was able to detect changes in the generator and mechanical asymmetries in steady-state condition, and it was able to do so using only the measured currents quantities. However, this method was most suitable for steady-state conditions as the convergence time was too long and it could only detect a deviation. It could not be used to more accurately detect what was causing the error.

Therefore, the focus of the project shifted to more accurately model faulty components to find specific characteristics of that fault. After a literature survey it was found that the turn-to-turn fault in the generator is one of the more common generator failures. This fault was then chosen as the failure to model in order to be able to early and accurately detect this type of fault. An analytical model of a generator with a turn-to-turn fault was developed and it was evaluated using a finite element model. The model was verified during various operation conditions and all showed acceptable agreement with the finite element model. The analytical model was also mathematically transformed into the synchronously rotating reference frame in order to study its behaviour in this reference frame. The reason for this was that it is not unusual to model a machine in the synchronously rotating reference for control purposes. There it was shown that a machine with a turn-to-turn fault behaves as an unbalanced machine. This effect, together with the knowledge that the machine will not have a perfect sine shaped back-EMF with a single frequency, was shown to be useful as an indication of that a turn-to-turn fault has occurred.

The fault only causes small amplitude variations in the current harmonics in the stationery reference frame which can be difficult to detect during operation, see Figure 3. It was found that monitoring the generator currents in the rotating reference frame was more efficient than to monitor the current in the stationary reference frame as the fault will cause new harmonics to appear in the rotating reference frame, see Figure 4.

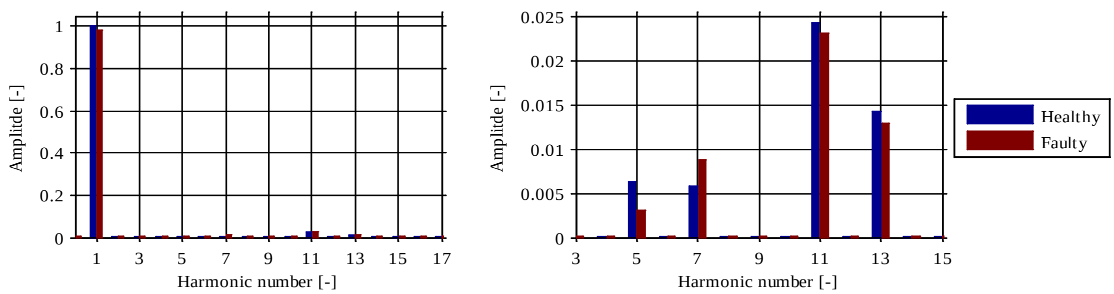


Figure 3: Normalised harmonics in the current of phase a from both the healthy and faulty machine models in the stationary reference frame

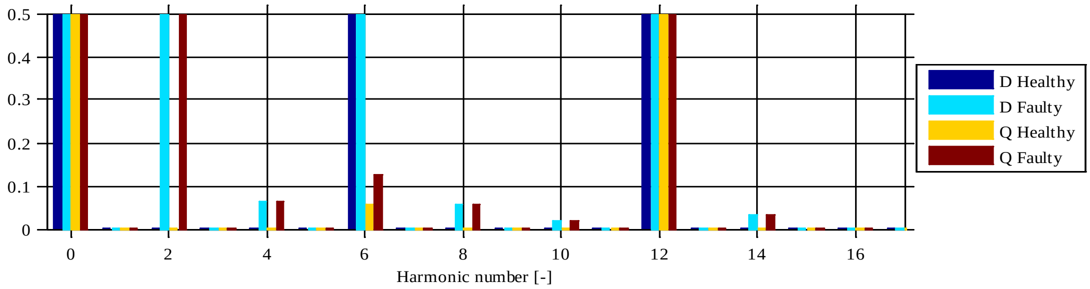


Figure 4: Harmonics content in the currents in the rotating reference frame from both the healthy and faulty machine models.

Fulfilment of SWPTC's goals

This project helped fulfilling SWPTC's goals such as development of the electric drive train, optimising the entire turbine and it is also contributed to the wind power technology knowledge in the engineering education.

It has also helped in looking into the possibilities of reducing the weight of the turbine using a more efficient electrical drive train and study if new materials can help reduce the weight. It has also helped increasing the life span of the turbines by better knowledge in the turbine condition due to the developed diagnostics method.

Deviations from project plan

The project was unable to verify the system model behaviour during grid disturbances because there were not any data available during this period, as the HVDC system installation was delayed.

Publications

1. J. Härsjö, *Modeling of PMSM Full Power Converter Wind Turbine with Turn-To-Turn Fault,* Licentiate Thesis, Department of Energy and Environment, Chalmers University of Technology, Gothenburg, Sweden, 2014
2. J. Härsjö, M. Bongiorno and O. Carlson, *Dually Fed Permanent Magnet Synchronous Generator Condition Monitoring Using Generator Current*, EWEA 2013 Annual Event, Vienna, February 2013
3. J. Härsjö, M. Bongiorno, S. Lundberg, Ola Carlson, *Permanent Magnet Synchronous Generator Inter Turn Fault Identification Using Stator Current Analysis*, 9th Ph.D. seminar in September 2013
4. P. Makolo, *Wind generator Co-simulation with fault case analysis,* Master's Thesis, Göteborg, 2013

External activities

- Visited the industry partners Göteborg Energi AB, ABB Corporate research and GE Global research.
- Attended EWEA 2013 in Vienna.
- Study visit to wind turbine Big Glenn, including nacelle visit.
- Attended EAWE 9'th Ph.D. seminar on Gotland.

Project title	Grid Code testing by VSC-HVDC
Project number	TG1-4
Organisation	Chalmers University of Technology, Electric Power Engineering
Project leader	Ola Carlson
Other participants	Nicolas Espinoza (PhD student)
Report for	2011-03-01 – 2014-09-30
Participating companies	ABB, Göteborg Energi, GE

Project description

The project will develop methods; carry out simulations and laboratory test/measurements for Grid Code tests with a Voltage Source Converter. The wind turbine/generator system with a full size converter will be the test object. The project will also make recommendations to and take part in the full scale tests of the GE Wind turbine in Göteborg. The result from the laboratory work and the full scale tests will be used to evaluate the proposed methods of testing. The result from the theory part and from the laboratory measurement will be a published in scientific papers and at conferences. Suggestions will also be made how to update the IEC-standards for Grid Code testing. The following Work Packages will be conducted in the project:

1. The different Grid Codes, from several countries, will be identified and the different requirements and tests will be categorized. The principle behaviour, including the control, of transistor converters and analogue gird simulators will be studied and documented.
2. Studies will be carried out to identify typical dips and swells occurring in the grid voltage. Real measured data is available in some extent. By former cooperation in the Nordic Grid projects this information will be available.
3. Simulation of the complete testing system with the wind turbine and the Voltage Source Converter (VSC) will be carried out. The VSC will emulate different grid situations according to the Grid Codes and the measurements from wind turbine installations.
4. Laboratory tests are planned to confirm the simulations done in WP3. The transistor voltage source converters will be designed and constructed at Division of Electric Power Engineering at Chalmers. The converter in Chalmers laboratory has the rated power of 50 kW. A typical wind turbine system consisting of a frequency converter and a generator will be used in the laboratory setup.
5. Field test at full power is planned in Göteborg, Sweden. Measurements with the ABB 8 MW HVDC-Light system, connected to a GE 4 MW wind turbine, will be used to validate the Grid Code testing procedures.

A part of the project will be to carry out a minor literature and conference survey of: The development of Grid Codes and the implementation in IEC standards. Also the development of voltage source converters in respect of rated power, voltage, space and price will be followed. Continual during the project there will be discussion, information exchange as well as minor design subtasks with the electric drive, optimal drive and control projects within the Centre.

Results

The setup shown in Figure 5 has been modelled in the time-domain simulation software PSCAD.

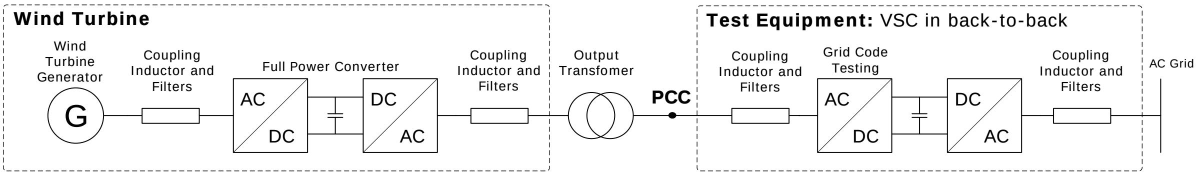
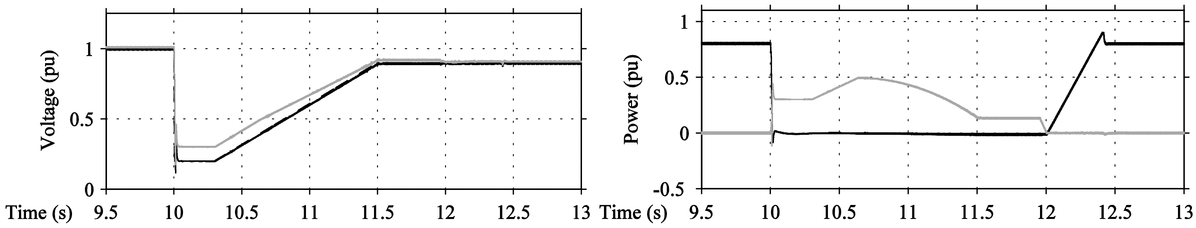


Figure 5: Wind turbine connected to a Back-to-back VSC –based testing equipment.

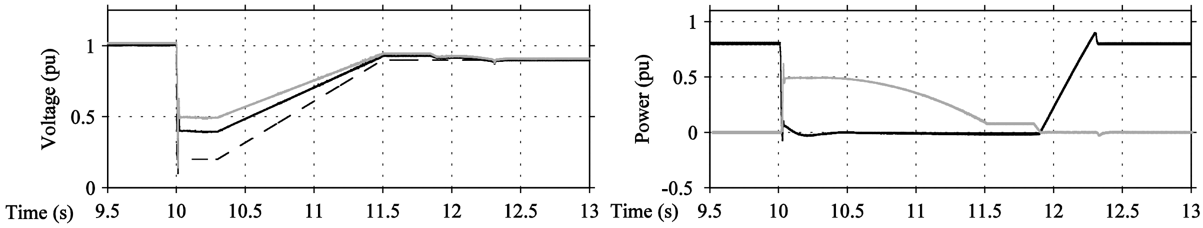
A discrete control algorithm has been developed in order to control the testing equipment. The grid-side VSC maintains the DC link voltage stable, while the collector-side VSC controls the voltage at the terminals of the wind turbine, including the emulation of the short-circuit impedance of the grid. A stability analysis has been carried out to identify sensitive settings between the wind turbine and the test equipment. Moreover, a mathematical model has been developed which resembles the dynamic of the wind turbine and HVDC system. The physical system of the HVDC AC filters, cable length and wind turbine AC filter is included, in conjunction with AC current controllers, AC voltage control in HVDC and DC voltage control in the wind turbine. The impact between the bandwidth of the controllers as well as variant parameters of the physical system has been studied using root locus analysis, step response characterization and overall stability analysis. Part of the results was included in a transaction paper. Full results will be included in the Licentiate Thesis. The manuscript is to be finished in December 2014.

Figure 6(a) shows the PCC voltage when a LVRT test is applied at the wind turbine. In this example, the PCC voltage is controlled in a stiff way, resembling an infinite grid. The wind turbine reacts by reducing active power production, and injecting reactive power into the grid, as shown in Figure 6(b). Observe that the PCC voltage is not affected by the control action of the WT. In Figure 7(a) is shown the system voltages when testing for LVRT. In this case, short-circuit impedance emulation is enabled in the voltage controller of the testing equipment. As shown in Figure 7(b), the wind turbine reacts by injecting reactive power into the grid. As a result, the PCC voltage is now affected by the operating condition of the wind turbine. Moreover, the PCC voltage is boosted due to the injected reactive power, resembling a weak grid.



(a) (b)

Figure 6: Stiff regulation of the system voltage during LVRT test: Plot (a): voltage magnitude at PCC (black), at wind turbine terminals (gray), and LVRT profile (dashed). Plot (b): wind turbine active (black) and reactive (gray) power.



(a) (b)

Figure 7: Emulation of grid impedance during LVRT: Plot (c): voltage magnitude at PCC (black), at wind turbine terminals (gray), and LVRT profile (dashed). Plot (d): wind turbine active (black) and reactive (gray) power.

A laboratory setup is under development during late 2014. It will represent the wind turbine and HVDC system in small scale (50 kVA / 400 V) as shown in Figure 8.

Figure 8: Laboratory setup: modelling of the back-to-back VSC and wind turbine.

During second half of 2014, the work time plan between licentiate and PhD seminar has been defined. It included the study of different converter topology for wind turbines, with special focus on efficiency; controllability; fault-tolerant operation; and the ability to fulfil the existing grid codes and to provide grid support during grid disturbances, as studied and documented during the first stage of the project.

Fulfilment of SWPTC's goals

This work has contributed to the development of grid code testing procedures for high power wind turbines. A high-class research was being conducted in this topic, considering a global perspective of technical requirements for interconnecting wind turbines enlisted in grid codes of different countries.

The testing equipment was a power electronic voltage source converter based testing device, capable to emulate the grid behaviour at the terminals of the wind turbine. The range and limitations of this equipment was being investigated in terms of stability issues. Dynamic mathematical models, simulation, laboratory experiments and field testing with the Big Glenn wind turbine will give us a better understanding about grid code development, actual and future testing procedures, and production and certification of complete wind turbines.

Deviations from project plan

Licentiate seminar has been delayed due to delays in laboratory setup, and because of the time employed in modifying the IEEE paper, especially during the two revision process during April-May and October 2014.

Publications

1. N. Espinoza, O. Carlson and M. Bongiorno, *Grid Code testing of Full Power Converter Based Wind Turbines Using back-to-back Voltage Source Converter System*, EWEA 2013 Annual Event, Vienna, February 2013

Submitted

1. N. Espinoza, M. Bongiorno and O. Carlson: *Novel LVRT Testing Method for Wind Turbines Using Flexible VSC Technology*, Special Issue on Large Scale Grid Integration and Regulatory Issues of Variable Power Generation of IEEE Transactions on Sustainable Energy. Status: 3rd revision of the manuscript has been submitted for peer review in 2014-10-24

External activities

- A visit to GE Global Research in Munich was conducted during the 7th and 9th of November, 2012.
- Nicolas Espinoza attended EWEA 2013 in Vienna.

Project title	Measuring of a wind turbine for verification of component design
Project number	TG1-5
Organisation	Chalmers University of Technology, Electric Power Engineering, Dynamics
Project leader	Ola Carlson
Other participants	Jan Möller, Magnus Ellsén, Stephan Struggl (PhD student), Saeed Asadi (PhD student), Håkan Johansson, Viktor Berbyuk
Report for	2011-03-01 - 2014-09-30
Participating companies	ABB, Göteborg Energi

Project description

This project looked towards to contribute to the reduction of early failures of mechanical and electrical components in wind turbines based on increasing knowledge obtained by measuring and analysis of the transmitted loads at those points (interfaces) where the mechanical and electrical components are attached to the turbine. More specifically the drive train and the generator system would be in focus of measurement campaigns.

The most important challenge is to develop procedures, complementary to the presently available standards and guidelines for mechanical and electrical loads measurements that enable validation of the drive train and the generator system models, and verification of their component design. These procedures will take into account specific design load cases and give recommendations for component modelling. The results of the project will be used for models validation and verification of drive train and generator system component design of a wind turbine, as well as for the Grid Code tests with a Voltage Source Converter.

Results

With the aim of making an inventory of the present day practice on turbine drive train and its component testing the work was focused on review of the literatures prioritising the existing standards and EU collaboration project reports. The review has been also done on the state-of-the-art on modelling and simulation of wind turbine drive train system. The obtained knowledge has been used to work with analysis, revision and developing of the test campaigns for GE 4.1MW wind turbine by taking into account requirements and needs for measurement data for running SWPTC research projects. General Electric and Göteborg Energi have supported the project to make measurements and receive measurement results from the 4 MW wind turbine during operation. To validate the mechanical as well as electrical quantities around 120 sensors were mounted in the wind turbine. The measurements were going on from winter 2012 to May 2013. All measurement results are stored on a fileserver at Chalmers, and the researchers in specific projects have access to the measurements.

The virtual model of the wind turbine drive train test rig has been created in CATIA V5, while the mathematical models were created in Matlab and FEA. The scaled down laboratory test rig of high-speed shaft subsystem of drive train of a wind turbine has been developed. ABB® has provided a considerable amount of equipment as in-kind contribution to the test rig development. A pair of 400V, 3 phase, and 6 pole induction motors capable of delivering shaft rotational speeds up to 1500rpm. The test rig has been instrumented by SKF WindCon system (Multilog system with corresponding software package (SKF @ptitude Observer®). A three day training and installation package were also offered by SKF, this enables Chalmers Test Rig project users to connect with SKF engineers to fully understand the installation, maintenance and operational uses of this system. The unique part of the test rig is the instrumented bearing housing. It was designed with springs, whose deformation can be used to calculate the forces acting on the bearings.

To support the SWPTC project “Stochastic Model Predictive Control of Wind Turbines” with accurate and fast sample wind measurements this project has mounted two new wind sensors on the wind measurement mast at Chalmers test station on Hönö. Wind measurements files are continually stored on Chalmers sever. The wind files are available for all SWPTC projects. The wind sensors have also been used to calibrate the LIDAR wind measurement device.

Fulfilment of SWPTC's goals

Developing of the test rig and the experimental study of loads in its functional components has been used for drive train model validation and accurate load prediction which lead to an increase of the life length of wind turbine components which contributes to SWPTC's goals.

Deviations from project plan

The work planned within the project has been completed.

Publications

1. S. Struggl, V. Berbyuk, H. Johansson, *Review on wind turbine with focus on drive train system modeling,* Wind Energy, pp. 1-24, 2014
2. M. Carlsson, E. Elofsson, J. Risö and D. Sandelind, *Virtuell design av en testrigg för ett vindkraftverk drivlina*, Bachelor Thesis, Göteborg, Sweden, 2012
3. S. G. McCann, *Design of Experiments and Analysis for Drive Train test Rig,* M.Sc. thesis 2013:30, ISSN 1652-8557, Chalmers University of Technology, Göteborg, Sweden, 2013
4. J. C. Squires, *Measurement System Design and Experimental Study of Drive Train Test Rig,* M.Sc. thesis 2014:36, ISSN 1652-8557, Chalmers University of Technology, Göteborg, Sweden, 2014

Submitted

1. S. Asadi, V. Berbyuk, H. Johansson, *Simulation and analysis of dynamics of a wind turbine drive train high-speed shaft subsystem test rig, In Proc.* 27th Nordic Seminar on Computational Mechanics, NSCM-27, KTH, Stockholm, 22-24 October, 2014

External activities

During the project work the collaborations have been established with NREL, Colorado, USA on Gearbox Reliability Collaborative project, with University of Mons, Belgium, and University of Aberdeen, UK, on master students' education relevant to wind power technology.

Project title	Reconfigurable LIDAR-system for wind measurement to support systems optimization of wind power plan
Project number	TG1-6
Organisation	WindVector AB
Project leader	Stellan Wickström
Other participants	Carl-Johan Cederstrand, Johan Sehlstedt, Lena Klasén
Report for	2011-01-01 to 2014-06-30
Participating companies	

Project description

In order to improve the performance of a wind power station, introduction of a LIDAR to measure the upcoming wind, distribution and speed, was proposed. By having a LIDAR with a configurable performance, the ability to predict the upcoming wind conditions was considered as an improvement with respect to the existing systems.

The current system, i.e. an anemometer mounted on the wind power nacelle, measures the direction and speed of wind with very good accuracy. However, the information is based on the wind conditions after the turbine blades and gives no warning in case of a strong upcoming wind gust. The wind conditions are also severely disturbed by the turbine blades, so it is likely that the wind conditions, let say 100m in front of the wind turbine, differs from after the blades where the anemometers usually are placed.

A design, manufacturing and delivery of a LIDAR with the possibility to measure wind in front of the turbine blades and in different directions to compensate for yaw and shear was decided as the main goal of the project. In addition, an installation on the 4MW wind power station Big Glenn in the Gothenburg harbour area in order to measure the upcoming wind conditions was an additional goal within the project.

The design was based on rather straightforward technology, with several modules and components from the telecom industry. The configurability consisted in having the possibility to measure the horizontal and the vertical direction of the upcoming wind simultaneously at 100m since the LIDAR emits in five different directions. However, it is also possible, by reconfiguration, to measure at shorter ranges in one or more directions. By further reconfiguration, even additional directions are possible to achieve.

By this configurability, it is possible for the first time to assess data from the LIDAR in order to simulate the influence of upcoming wind distribution in the control loop for the wind power station.

Summary goal for the project

- What aspects of mounting on the nacelle that have to be considered, and how mounting affects data quality.
- How geometry, distance and number of measuring points affect information quality into the control loop.
- What degree of data processing is needed to extract sufficient data duality for the control loop.

The project, which was a part of the Control project (TG1-1) run by Chalmers, has cooperated with Chalmers, the division for Automatic control, Automation and Mechatronics.

Results

A LIDAR to measure the speed of wind has been designed, constructed and, eventually mounted on the Big Glenn.

Initially, the first test of the LIDAR, performed roughly one year after the start of the project, showed promising results when testing on aerosols. However, it was later understood that the aerosols at that time were small ice crystals with high reflectivity, indicating the sensitivity for the LIDAR was very poor.

Further work disclosed several sources to the lack of sensitivity and once these shortages were erected, it was possible to measure against regular aerosols and thereby measuring the speed of wind. Additional signal processing algorithms were implemented and tested in the lab and in the field in order to improve the sensitivity.

In order to secure measuring, several field tests were performed at the Chalmers test station on the island Hönö. Results from these tests showed a very good correspondence between the results from the test station anemometer and the LIDAR. Eventually, the LIDAR was mounted on Big Glenn and instantly provided wind speed data by the remote data system installed by WindVector.

After some months in operation, it was clear the performance of the LIDAR was poor and only occasionally delivered reliable wind data. In some cases the processor board stopped to work due to overheating. But the most critical result during the installation period on Big Glenn was the suddenly reduced performance. The conclusion from WindVector was that the humidity in the air went down to too low level for the LIDAR to be able to detect the aerosols. The reasons are likely the following.

To low sensitivity in the system due to losses and actions taken to improve the system:

- New mirrors are installed and has showed an improvement of 3dB
- The electrical shielding of the device will be increased in order to be able to run the more sensitive algorithms
- Common mode voltage will be suppressed by upgraded internal electrical architecture.

The LIDAR has a five-beam performance and spreads the laser beams as for a dice with an individual separation of 20 degrees. The laser beams are focused at 100m and the speed of wind is measured in a volume limited to 10 meters. Due to eye safety considerations, only four of the laser beams were active during mission on the Big Glenn.

Fulfilment of SWPTC's goals

The overall goal of the project is to provide knowledge of:

- turbine load reduction,
- turbine weight reduction,
- turbine cost reduction,
- how much turbine effect can be increased

when a LIDAR is in the control loop for the wind turbine.

The SWPTC's goals have only partially been fulfilled since the LIDAR, installed on the Big Glenn, needs further improvements to deliver reliable data. And in addition, the data delivered from the LIDAR arrived too late for a reasonable evaluation within the control project since the development of the LIDAR was severely delayed.

Deviations from project plan

The most critical deviation from the project plan was of course the severe delay in installing the LIDAR on Big Glenn. In addition, the data is currently too unreliable due to lack of sensitivity and, most likely, EMC noise from the generator on Big Glenn.

Due to EMC disturbances the LIDAR has suffered from on Big Glenn, as described in the annual report for TG1-6, the amount of data from the different meteorological conditions is very limited. However, test with an unconfirmed visibility and with the LIDAR installed on Big Glenn, showed an acceptable performance down to 60-70% RH. Below this figure, the test result was unreliable. Test in the WindVector noise free laboratory, showed promising results down to 40%RH, without introducing any improvements of sensitivity or sustainability against external induced noise.

Publications

No publications are produced or published.

External activities

No external activities are reported.

Project title	Analysis of LIDAR data in meteorological envelope
Project number	TG1-7
Organisation	WindVector AB
Project leader	Stellan Wickström
Other participants	Carl-Johan Cederstrand, Johan Sehlstedt, Lena Klasén
Report for	2014-01-01 to 2014-09-30
Participating companies	

Project description

One of the findings during project TG 1-6 was how the analogue LIDAR signals vary with shifting meteorological conditions. The most important factor affecting the quality of analogue data is the visibility. Clear weather with high visibility will generate more uncertain data than rainy weather. Thus, in worst case, this implies that when a wind speed figure is being presented by the LIDAR system, a false impression of certainty can be present in case the wind speed is generated by very uncertain analogue data.

In order to assess the commercial benefit of investing in LIDAR sensors for operation of wind turbines, it is therefore of interest to have some statistical assessment, mainly to investigate how many days per year a LIDAR can be used from a data quality perspective. Although the LIDAR system is operational all year around, there might be a number of days where the LIDAR data is of low quality and thus uncertain.

The goal of this project is to:

1. Gain knowledge on the typical visibility characteristics.
2. Perform evaluation of LIDAR data quality at a number of visibility ranges based on measurement gathered over a longer time period.
3. As a result of 1) and 2) above assess how often and at what visibility ranges LIDAR data is unreliable.

The project, which is an extension of the project TG1-6, aims to bring knowledge of the variation of different visibilities at different locations in Sweden. In addition, the LIDAR will be tested under some different visibilities in order to evaluate the conditions for reliable test data from the LIDAR.

Results

A backscatter algorithm for evaluation of signal strength has been designed and integrated in the LIDAR. The purpose of the algorithm is to provide a tool for monitoring of reflected laser energy in different weather conditions.

A second task has been to identify the critical meteorological parameters that affect reflectivity of laser signals. Analysis of measured wind data from Hönö and Big Glen indicate a strong correlation between data quality and relative humidity (RH). These observations are partly supported by several research programs. For this study, this correlation is of great use as humidity data can be obtained from most meteorological stations. A literature study of research reports in this field also shows a strong correlation between data quality and concentration of dust particles, which is not surprising.

Fulfilment of SWPTC’s goals

The overall goal of the project in the Academic perspective was to provide:

- Knowledge to SWPTC about possibilities and limitations of LIDAR technology as a tool to gather predictive wind information
- Knowledge to SWPTC on typical visibility characteristics and the impact on LIDAR data quality

The SWPTC’s goals have only partially been fulfilled since the LIDAR, installed on the Big Glenn, needs further improvements to deliver reliable data.

Deviations from project plan

Due to EMC disturbances the LIDAR has suffered from on Big Glenn, as described in the annual report for TG1-6, the amount of data from the different meteorological conditions was very limited. However, test with an unconfirmed visibility and with the LIDAR installed on Big Glenn, showed an acceptable performance down to 60-70% RH. Below this figure, the test result was unreliable. Test in the WindVector noise free laboratory, showed promising results down to 40%RH, without introducing any improvements of sensitivity or sustainability against external induced noise.

Tests from Big Glenn show that the negative impact in signal strength from moderate rain is negligible, however does rain affect the possibilities to measure turbulence as the LIDAR most likely obtains its data from the rain drops.

After correction of the current sensitivity and EMC problems, the next step is to perform tests at low RH (<35%) and during snowfall. As a last step, a statistical analysis will be performed to translate the measured data to availability.

Publications

No publications are produced or published.

External activities

No external activities are reported.

Project title	Aerodynamic loads on rotor blades
Project number	TG2-1
Organisation	Chalmers University of Technology, Fluid Dynamics Division
Project leader	Professor Lars Davidson
Other participants	Hamidreza Abedi (PhD student)
Report for	2011-01-01 - 2014-09-30
Participating companies	GE

Project description

The aim of the project is to develop computational methods for predicting unsteady aerodynamic loads on wind turbine rotor blades. The focus of the project is to handle transient loads by the Vortex Method in which tabulated lift and drag coefficients are used.

The three different prescribed wake approaches (lifting line, lifting surface, panel method) of steady vortex method application for wind turbine's aerodynamic loads have been developed. Further, a time-marching vortex lattice free wake (VLFW) has been developed which can be used to predict the wind turbine aerodynamic loads for different operating conditions such as turbulent inflow and yaw condition. The VLFW method is based on the potential, inviscid and irrotational flow where its potential solution is coupled to the tabulated airfoil data and a semi-empirical model to take into account the viscosity and the dynamic stall effects, respectively. In addition, a module has been added to the developed vortex code for increasing its application range by handling all type of turbine components movements (both translation and rotation) through the simulation such as blade pitch regulation, cone angle, shaft tilt, nacelle and etc.

The implemented vortex method has been validated by comparison with the Blade Element Momentum (BEM) method, the GENUVP code by National Technical University of Athens (NTUA), Hönö turbine measurement data and MEXICO wind tunnel measurements.

There was a cooperation with the project "Hönö turbine properties and thrust vector at yaw misalignment" (financed by Energimyndigheten), where the power generation and thrust vector at significant yaw misalignment was studied (see Publications section). The results were compared with the experimental data provided by Scandinavian Wind AB.

The present project is currently cooperating with the project TG2-2 *Fatigue Loads in Forest Regions*. The outcome of the TG2-2 project, turbulent fluctuation in atmospheric boundary layers both with and without forest, is used as the unsteady incoming flow in the present project.

The next step will be coupling of the vortex method code to the aeroelastic solver, called ViDyn and FreeDyn through an interface prepared by Scandinavian Wind AB. This will mainly be achieved through interaction with other on-going projects within SWPTC such as the Wind Turbine Drive train project and the Validation of Structural Dynamics project.

Results

The results have been presented in six papers (see Publications section) and supervising two Master Theses as below.

The application of vortex method for wind turbine load calculation has been examined by the developed VLFW code and the predicted aerodynamic loads have been compared with the other approaches such as the BEM method and CFD.

The developed VLFW code has been used to study the deviation of thrust vector relative to rotor shaft for different yaw misalignments and wind speeds where the results have been compared with the BEM method and experimental data of Hönö turbine.

Moreover, the potential solution of the VLFW code has been coupled to the tabulated airfoil data for the wind turbine load calculation. In addition, a semi-empirical model, called Extended ONERA model has been added to account for the dynamic stall effects.

Fulfilment of SWPTC's goals

In the project, methods for more accurate prediction methods of aerodynamic loads were developed. This will lead to:

1. lighter wind turbines
2. increased lifetime of wind turbines
3. reduced maintenance costs

Deviations from project plan

There is no deviation from the project plan.

Publications

1. B. Montgomerie, *A Contribution to Wind Turbine Wake Dynamics Algorithms*, Wake Conference June 8-9, 2011; Gotland University, Visby, Sweden.
2. H. Abedi, L. Davidson, S. Voutsinas, *Vortex Method Application for Aerodynamic Loads on Rotor Blades*, EWEA 2013: Europe's Premier Wind Energy Event, Vienna, 4-7 February 2013.
3. H. Abedi, L. Davidson, S. Voutsinas, *Development of Vortex Filament Method for Aerodynamic Loads on Rotor Blades*, Licentiate thesis, Göteborg, Chalmers University of Technology, 2013.
4. H. Abedi, L. Davidson, S. Voutsinas, *Development of free vortex wake method for aerodynamic loads on rotor blades*, EWEA 2014, Europe's Premier Wind Energy Event, 10-13 March 2014, Barcelona, Spain.
5. H. Abedi, L. Davidson, S. Voutsinas, *Development of free vortex wake method for yaw misalignment effect on the thrust vector and generated power*, 32nd AIAA Applied Aerodynamics Conference 16-20 June 2014, Atlanta, USA.
6. K. M. Schweigler, *Aerodynamic Analysis of the NREL 5-MW Wind Turbine using Vortex Panel Method*, Department of Applied Mechanics, Division of Fluid Dynamics, Chalmers University of Technology, Göteborg, Sweden, 2012.
7. J. Norli,n C. Jäarpner, *Fluid Structure Interaction on Wind Turbine Blades*, Department of Applied Mechanics, Division of Fluid Dynamics, Chalmers University of Technology, Göteborg, Sweden, 2012.

Submitted

1. H. Abedi, L. Davidson, S. Voutsinas, *Enhancement of Free Vortex Filament Method for Aerodynamic Loads on Rotor Blades*, Proceedings of ASME 2014 International Mechanical Engineering Congress and Exposition, November 14-20, 2014, Montreal, Canada.
2. H. Abedi, L. Davidson, S. Voutsinas, *Numerical Studies of the Upstream Flow Field around a Horizontal Axis Wind Turbine*, 33rd ASME Wind Energy Symposium, 5-9 January 2015, Florida, USA.

External activities

- Aerodynamics for wind turbines, 26 May 2011, Chalmers University of Technology.
- Wake Conference 8-9 June 2011, Gotland University, Visby, Sweden.
- Wind energy aerodynamics-icing and de-icing of WT blades, 5 September 2011, Chalmers University of Technology.
- 7^{th} PhD Seminar on Wind Energy in Europe, 26-28 October 2011, Rotterdam-Netherland.
- Vindforsk 2012, 18-19 January 2012, Chalmers University of Technology.
- PhD Course, Vortex Method Application in Aerodynamics, 13-17 February 2012, Delft University, Netherland.

- Visiting National Technical University of Athens (NTUA), from 4 March to 8 April 2012, Athens, Greece.
- 8th PhD Seminar on Wind Energy in Europe, 12-14 September 2012, Zurich, Switzerland.
- Vindindkraftsforskning i fokus 2013, 16-17 September 2013, Chalmers University of Technology, Sweden.
- High Performance Computing Course, April-May 2013, Chalmers, Sweden.
- Visiting National Technical University of Athens (NTUA), from 11 November to 24 December 2012, Athens, Greece.
- Visiting National Technical University of Athens (NTUA), from 24 March to 07 April 2013, Athens, Greece.
- Visiting National Technical University of Athens (NTUA), from 14 March to 21 April 2014, Athens, Greece.

Project title	Fatigue Loads in Forest Regions
Project number	TG2-2
Organisation	Chalmers University of Technology, Applied Mechanics
Project leader	Lars Davidson
Other participants	Bastian Nebenführ (PhD student)
Report for	2012-07-01 - 2014-09-30
Participating companies	SKF, Teknikgruppen, WindVector AB, Vattenfall, DIAB

Project description

As a consequence of the development of wind turbines with hub heights above 100m, wind turbines can operate efficiently, even in the relatively low wind speeds above forests. Placement of wind turbines in forest regions has hence become an appealing option. Moreover, permits are usually granted more easily than for wind parks close to residential areas. However, the flow above forests is characterised by strong wind shear and strong turbulence, which induce high aerodynamic loads on the wind turbines. Due to that, faster material fatigue, more frequent maintenance and a reduced lifetime for wind turbines exposed to winds in forested regions can be expected.

The present project aims at using a high-fidelity CFD method, called Large-Eddy Simulation (LES) for the prediction of the atmospheric boundary layer (ABL) approaching the wind turbine. We directly include the influence of the forest on the ABL in our simulations. Both, wind shear and turbulence are inherent in the flow solution and are stored in a database for subsequent use as input in wind turbine load calculations. We are able to perform these load calculations in-house, using the state-of-the-art structural wind turbine simulation tool FAST. Additionally, load calculations can be performed by our project partner, Teknikgruppen, using their tool, ViDyn.

In order to validate the CFD results, measurement data from the Ryningsnäs test site are available.

Results

A method for simulating atmospheric boundary layers under the direct influence of a forest has been implemented in an in-house CFD code. The implementation included the effect of the Earth’s rotation (Coriolis effect), the possibility to simulate various stability classes of the ABL (surface heating/cooling -> unstable/stable ABL) and the forest model itself. The forest was modelled as an increased drag force on the flow, similar to a porous medium.

The implementation of the forest model has been validated against test cases available in the literature and was found to perform well. It was found from several simulations that, for now, both domain size and grid resolution are the limiting factors in the simulations. Using the available in-house code, we were constrained to fairly coarse grids and limited domain sizes. This constraint should be removed, once a new, parallel version of the in-house code is available (work in progress).

Initially, the results of our simulations seemed to suffer under the limited grid resolution. For that reason, numerical experiments were conducted in which forcing from synthetic turbulence was added at the canopy top in order to increase the resolved turbulent fluctuations. A summary of some of these tests were presented at the 9th PhD Seminar on Wind Energy in Europe.

Later on, the idea of forcing at the canopy was discarded again, since good agreement with the measurement data was obtained even with the rather coarse simulations.

One major concern was to simulate the atmospheric boundary layer over the forest for different thermal stratifications (that can be interpreted as simplified weather conditions). A study has been carried out simulating six different regimes of thermal stratification, ranging from unstable to very stable conditions. The different regimes were identified from the available field measurement data at Ryningsnäs. The influence of two different sub-grid scale models on the results was studied. This work has been submitted for publication in a scientific journal.

As an attempt to enable quasi-steady LES of the atmospheric boundary layer in unstable thermal stratification, a method to balancing the temperature equation has been proposed. With the help of this technique, the simulation results were considerably improved, mainly in terms of the prediction of the wind turning angle and velocity variances. Also this work is to be submitted for publication.

Cooperation with the project TG2-1 *Aerodynamic loads on rotor blades* is on-going. Atmospheric turbulence from Large-Eddy simulations has been supplied for the use in that project.

During an extended visit to Northeastern University in Boston (April – July, 2013), a reduced order model of the NREL 5MW standard wind turbine were developed. Using this model and ViDyn, fatigue loads for the NREL standard wind turbine were calculated based on two LES: one with and one without a forest. The direct comparison of the two cases with and without forest showed that both turbulence intensity and wind shear are increased by the presence of the forest. It was further shown that the IEC design criteria were largely exceeded and the tower base bending moment was increased in the forest case. Moreover, the simple reduced order model compared favourably to the results obtained with ViDyn. The results of this work were published at the Computational Wind Engineering (CWE) conference.

Two LES, with and without forest, were also investigated in terms of turbulence. Once again, a large increase in both wind shear and turbulence intensity was found in the simulations with forest. A comparison of turbulence statistics indicated the importance of intermittent turbulence in the forest case. This work was presented at the ETMM10 conference.

Fulfilment of SWPTC's goals

In the project, methods for more accurate prediction methods of aerodynamic loads in forest were developed. This will lead to:

- lighter wind turbines
- increased lifetime of wind turbines
- reduced maintenance costs

Deviations from project plan

No deviations.

Publications

1. B. Nebenführ, L. Davidson, *Large-Eddy Simulation for Wind Turbine Fatigue Load Calculation in Forest Regions*. Proceedings of 9th PhD Seminar on Wind Energy in Europe, September 18-20, 2013, Uppsala University Campus Gotland, Sweden
2. B. Nebenführ, I. Carlen, L. Caracoglia, L. Davidson, *Development of a reduced-order model for wind turbine response to atmospheric turbulence in forest regions*, Proceedings of 6th International Symposium on Computational Wind Engineering, Hamburg, Germany, 8-12 June, 2014
3. B. Nebenführ and L. Davidson, *Influence of a Forest Canopy on the Neutral Atmospheric Boundary Layer -- a LES Study*, *ETMM10:* International ERCOFTAC Symposium on Turbulence Modelling and Measurements, Marbella, Spain, 17 - 19 September, 2014
4. B. Nebenführ, Oral presentation at ECCOMAS 2014, 6. European Conference on Fluid Dynamics (ECFD VI), July 20-25, 2014, Barcelona, Spain.
5. B. Nebenführ, Oral presentation at 9th PhD Seminar on Wind Energy in Europe, September 18-20, 2013, Uppsala University Campus Gotland, Visby, Sweden.
6. B. Nebenführ, Oral presentation at 10th International ERCOFTAC Symposium on Engineering Turbulence Modelling and Measurements, September 17-19, 2014, Marbella, Spain.

Project title	Wind turbine drive train dynamics, system simulation and accelerated testing
Project number	TG3-1
Organisation	Chalmers University of Technology, Applied Mechanics
Project leader	Viktor Berbyuk
Other participants	Stephan Struggl (PhD student: III-2011 - XII-2012), Saeed Asadi (PhD student: from March 2013), Lei Xu (postdoc: VI-2011-VII-2012), Tomas Grönstedt, Håkan Johansson, Jan Möller
Report for	2011-01-01 - 2014-09-30
Participating companies	ABB, SKF, GE

Project description

To facilitate the design and production of highly efficient and reliable drive trains, the proposed project deals with the development of methods, mathematical models and validated computational tools for advanced analysis of drive train dynamics and load transmission in multi-MW wind turbines. The project TG3-1 can be summarized by its three goals.

First – methods, models and validated computer tools for advanced analysis of drive train dynamics and load transmission to ensure correct dimensioning for each drive train component of multi-MW wind turbines.

Second – a systematic procedure for the validation of the developed deterministic as well as nondeterministic models using experiments tailored for the prediction of life characteristics and to develop methodology for drive train accelerated testing of multi-MW wind turbines.

Third – system integration environment and an integrated system simulation tools (Version 0.1) for robust and cost-effective design of modern multi-MW wind turbines.

Results

Within the first project goal, the review of the state-of-the-art on modelling and simulation of wind turbine drive train system dynamics has been done and was published in [1]. A model to study torsional drive train vibration dynamics of a generic indirect drive multi-MW wind turbine has been developed. The main focus lay on developing a fully parameterized computational model of a multi-stage gearbox which fulfils the requirement of a proper gear dynamic representation appropriate for multibody formalism as well as the requirement to be computationally efficient. Two different strategies for modelling the gear contact were studied and compared in time domain. An analysis of a multi-stage gearbox together with a generator load and a turbine specific nondeterministic excitation was carried out. The obtained results showed that for deep understanding the complex phenomena occurring in the drive train system with gearbox, higher hierarchical modelling levels are necessary. Focusing on the contact problem itself requires more sophisticated contact models than the one developed. A combination of tools for macro and micro-scale investigations is necessary which might be difficult to implement. The computational demands of such models can be very high which makes it time consuming running parameter studies to find optimal system structural parameters. More details can be found in [2]. For modelling of drive train dynamics it is important to understand load interfaces, i.e. the rotor load interface (RLI), the generator load interface (GLI) and the tower load interface (TLI). A numerical algorithm has been developed and implemented in MATLAB for evaluation RLI, GLI and TLI. Two techniques for calculating the aerodynamic forces were proposed based on Uniform Forces Distribution approach and Real Forces Distribution method. A series of simulations under different wind conditions according to IEC standard have been performed. RLI model has also been validated against field measurements. More details can be found in [3, 4]. As a continuation of previous work on modelling of gear contact, 3D FE-models analysing the transmission error for angular and parallel misalignment has been studied and details of the results obtained were published in [5]. The mathematical and computation models have been developed to determine and analyse the torsional and flexural vibrations in high-speed shaft subsystem of a wind turbine drive train. The models were targeted to the developed physical test rig of scaled down drive train (see Figure 9). More details about the developed test rig are available in the report on TG1-5 project and in [6-9]. The models and the test rig were used to study vibration dynamics, system misalignments and how the misalignments affect the internal dynamics of drive train functional components (bearings, shaft couplings, others) for different load cases, e.g. emergency shutdown. Validation of mathematical models of drive train and its components was also in focus. Some results of computer simulations of vibration dynamics of high-speed shaft subsystem of drive train was published in [6].

Figure 9: The test rig of high-speed subsystem of drive train of a wind turbine

To understand the trend in upscaling of wind turbines and study their characteristics a database has been created. It includes more than 230 different wind turbines from 34 manufacturers with a power output between 0.1 and 15 MW and a rotor diameter between 12.8 and 200 m. A model was created with the aim of predicting the main characteristics of future upscaled wind turbines based on information included in the database. The model had several inputs, such as the rotor diameter, wind speed and air density, and it gave as outputs other characteristics of the wind turbine, such as the expected rated power output, the weight and the dimension of different parts. More details about the model have published in [10].

Within the second project goal, a model for the drive train of a direct drive turbine relevant to GE 4.1 MW “Big Glenn” has been developed and was to some extent verified towards previous simulations carried out by Teknikgruppen. The studies investigated the model detail effect on bearing fatigue life calculations, and to what extent the assumed wind field turbulence affect the estimated bearing life in certification analyses. A method to estimate the risk of failure in a wind turbine bearing after 20 years of service under varying wind conditions was developed. It was found that a quasi-static model is sufficient for estimating the bearing life of main support bearings in the “Big Glenn” concept, but not for the bearings carrying the generator stator. It was also found that under normal operating conditions, for the main bearing winds at about 11 m/s are the most damaging because of the high (axial) thrust before blade pitch reduce the thrust at higher wind speeds. The obtained results has been presented on EWEA2014 Conference and published in [11]. As a model problem for accelerated testing, the effect of misalignments on the fatigue life of disc couplings was investigated. Several experiments have been carried out to determine parameters of shaft coupling obtained from SKF.

Within the third project goal, a system simulation tool called FreeDyn has been developed. Since it is a quite complex task to build wind turbine simulation tools as due to the very different competences needed (aerodynamics, solid mechanics, control, electronics) the main aim of FreeDyn was to define a good interface between different component models (blade, tower, nacelle, control unit etc.). The definition of interface and data transfer was done as a first subpart. As a second part, more realistic component models have been developed for blades and aero-elastic interface, based on co-rotational frame. To allow for fast execution and avoid proprietary software, the simulation code is written in FORTRAN. Besides the modelling itself, the optimisation tool has also been selected. The DAKOTA (Design Analysis Kit for Optimization and Terascale Applications) is an open-source code developed by Sandia National Laboratories and it is capable of design of experiment study, optimisation, etc.

Fulfilment of SWPTC’s goals

The long-term outcome was numerical methods, simulation tools and procedures that can be used to improve precision in the prediction of loads acting on the turbine drive train functional components. This is crucial in the endeavour to reduce weight of the drive train components, as well as predicting the effect of changes in other components, such as the blades being lighter from change in design and/or material. Engineering education with focus on different areas of wind turbine technology is important and contributes for personnel development for wind industry. During the reporting period the master course “Structural Dynamics Control” has been further developed and supported with a new textbook [12]. Several Bachelor and Master projects have been completed successfully involving students from different universities (see Ref. [3-5, 7-10]).

Deviations from project plan

Within the second project goal, the problem of required model detail (often sensitive information) to be able to compare to measurements done lead to a shift in research focus to instead assessing model predictions of fatigue life. Also due to available data and information supplied to SWPTC, only a direct drive wind turbine concept has been studied. Also, the study was limited to normal operation. Within the third goal, it turned out not possible within the frame of allocated resources to include sufficiently advanced component models to be able to run simulations that could be verified against other codes.

Publications

1. S. Struggl, V. Berbyuk, H. Johansson, *Review on wind turbine with focus on drive train system modeling,* Wind Energy, pp. 1-24, 2014
2. S. Struggl, V. Berbyuk and H. Johansson, *Wind turbine drive train vibration with focus on gear dynamics under nondeterministic loads*, Proceedings, International Conference on Noise and Vibration Engineering, ISMA2012; International Conference on Uncertainty in Structural Dynamics, USD2012, Belgium, 17 - 19 September 2012*, pp. 4421-4434. ISBN/ISSN: 9789073802896*
3. F. Baldo*, Modeling of Load Interfaces for a Drive Train of a Wind Turbine*, Master’s Thesis 2012:10, ISSN 1652-8557, Chalmers University of Technology, Göteborg, Sweden, 2012
4. B. Jiang, *Modelling of Dynamics of Driveline of Wind Station: Implementation in LMS Image AMESim Software.* M.Sc. thesis 2010:38, ISSN 1652-8557, Chalmers University of Technology, Göteborg, Sweden, 2010
5. M. Irfan, *Meta modeling of transmission error for spur, helical and planetary gears for wind turbine application*, Research report, Department of Applied Mechanics, Chalmers University of Technology, Göteborg, Sweden, ISSN 1652-8549; 2013:06, 2013
6. J. C. Squires, *Measurement System Design and Experimental Study of Drive Train Test Rig,* M.Sc. thesis 2014:36, ISSN 1652-8557, Chalmers University of Technology, Göteborg, Sweden, 2014
7. S. G. McCann, *Design of Experiments and Analysis for Drive Train test Rig.* M.Sc. thesis 2013:30, ISSN 1652-8557, Chalmers University of Technology, Göteborg, Sweden, 2013
8. M. Carlsson, E. Elofsson, J. Risö and D. Sandelind, *Virtuell design av en testrigg för ett vindkraftverk drivlina*, Bachelor Thesis, Göteborg, Sweden, 2012
9. P. de Lara García, *Wind Turbine Database: Modelling and analysis with focus on upscaling.* M.Sc. thesis 2013:21, ISSN 1652-8557, Chalmers University of Technology, Göteborg, Sweden, 2013
10. H. Johansson, V. Berbyuk, *Statistical analysis of fatigue loads in a direct drive wind turbine,* Online proceedings of the European Wind Energy Association (EWEA) Annual Event 2014, 2014
11. V. Berbyuk, *Structural Dynamics Control, Second Edition,* Department of Applied Mechanics, Chalmers University of Technology, Göteborg, Sweden, Skrift 2014:01, 2014, 271 pages

Submitted

1. S. Asadi, V. Berbyuk, H. Johansson, *Simulation and analysis of dynamics of a wind turbine drive train high-speed shaft subsystem test rig, In Proc.* 27th Nordic Seminar on Computational Mechanics, NSCM-27, KTH, Stockholm, 22-24 October, 2014

External activities

During the project work new national and international collaborations have been established, namely with NREL, Colorado, USA on Gearbox Reliability Collaborative project, Scandinavian Wind AB, Teknikgruppen AB, University of Mons, Belgium, and with University of Aberdeen, UK.

Project title	Development of Compound Bearing Concept
Project number	TG3-2
Organisation	Swerea
Project leader	Sven Haglund
Other participants	Hans Kristoffersen, Karin Frisk
Report for	2013-03-13 – 2013-09-30
Participating companies	SKF, Erasteel, Bodycote

Project description

The aim of the project is to suggest materials combinations for a compound bearing with a low-cost base material and a high performance material in the raceway, especially designed for demanding wind turbine applications. The raceway is produced by a powder metallurgical route and HIP-ed together with the base material to a single bearing washer.

Summary of the project activities:

- Identify the demands on the materials in the raceway and in the core.
- Equilibrium and kinetic simulations of the chemical reactions between selected core and raceway materials during HIP-ing are performed. Equilibrium calculations will give the answer to what reactions that may occur and some materials combinations may be excluded already at this stage. Kinetic simulations will show how far the alloying elements may diffuse and how far the reactions will completed.
- FEM-simulation of residual stresses formed during the heat treatment of the compound washer. Factors influencing the residual stresses will be identified. Conditions causing tensile stresses in the raceway or too large stresses during cooling risking interface delamination will be avoided.
- HIP-experiments on selected materials combinations will be performed on laboratory specimens. The specimens are carefully studied both metallographical and chemically.
- Contact fatigue properties of a raceway material will be evaluated. Due to time limitations within the project this is not done on compound washers but on washer in solid raceway material made by powder metallurgy so that the defect populations are comparable to defects in an actual compound bearing. The tests are performed as bearing tests.
- A prototype bearing washer will be manufactured within the project.

Results

Equilibrium and kinetic simulations were carried out with three raceway materials in combination with nine different raceway materials. The most promising combinations had the same carbon activity in raceway and core materials at HIP-temperature in order to avoid long range diffusion of carbon. Carbon diffusion could give local changes in Ms-temperatures as well as dissolution or precipitation of carbides which could cause cracking or poor mechanical properties. 14 of the combinations were considered suitable.

The FEM simulations showed that the Ms-temperature of the core should be higher than the Ms-temperature of the raceway material in order to induce compressive residual stresses in the raceway. The simulations also showed that the raceway thickness should be as thin as possible in order to maximise the compressive residual stresses in the raceway and to minimise the tensile stresses in the core

Four materials combinations were tested in small scale HIP experiments. The investigated combinations, M50//SS2244, XD15NW//Ovako 225A, APZ10//Ovako 225A and APZ10//Ovako 277L all showed good bonding between core and raceway material and no unwanted precipitation in the interface. All combinations were found suitable for further studies. The experimentally measured concentration profiles agreed well with calculations.

Demonstrator compound washers are being manufactured in the combinations M50 (raceway) // SS2244 (core) and XD15NW (raceway) / Ovako225A (core). The manufacturing was not completed at the time of writing this annual report.

Deviations from project plan

Manufacturing of test rings and demonstrator washers were delayed partly due to high production load on Bodycote and partly to unexpectedly long time for machining of test ring.

Publications

1. S. Haglund, K. Frisk, S. Caddeo Johansson, H. Kristoffersen, *Development of Compound Bearing Concept for Wind Power Applications, part 1*, Swerea KIMAB report

Submitted

1. K. Frisk, C. Luo, S. Caddeo Johansson, S. Haglund, N. Petterson, I. Strandell, *Compound Materials by PM-HIP*, Accepted for publication in Powder Metallurgy

External activities

Project title	Validation of Wind Turbine Structural Dynamics Models
Project number	TG4-1
Organisation	Chalmers University of Technology, Applied Mechanics
Project leader	Thomas Abrahamsson
Other participants	Majid Khorsand (PhD student)
Report for	2011-06-01 - 2014-09-30
Participating companies	GE

Project description

In this project, the validity of structural dynamics models of wind turbines is studied. The model validity considered is of hierarchical dual level. On one hand, a detailed structural dynamics model needs to be substantiated by good correlation between experimental results of wind turbine testing and theoretical simulation results using that model. One the other hand, after that detailed model has been validated, a model of significantly lower order based on the detailed model needs to be validated by a good model-to-model correlation. With the connection between models, this implies that also the lower-order model is implicitly validated by testing.

The use of two model levels is strongly motivated by their different focal points. The detailed structural dynamics model, most often a finite element model, is motivated by its strong connection to the observed fundamental physical laws. The purpose of this model is to give real physical insight to observations made during physical testing. Such models can be used to study the impact of backlash, elastic material properties, geometrical dimensions, material density variation, temporal and spatial load variations, component dynamics, properties of structural joints, temperature changes, wing twisting, non-linear effects, etc. The low-order model is motivated by its fast evaluation. The main purpose of this model, often called a black-box model, is to give a correct representation of the stimuli-to-response characteristics of the system in an efficient simulation environment. Such low-order model is highly suitable for system optimization and probabilistic design that rely on fast, accurate and efficient calculations and simulations. In the wind turbine application, the stimuli are the loadings from wind, waves, mechanical and electrical braking, etc. The response is the structural motion in component interfaces, stresses and strains at critical sections, wing deflection and twist, etc. The low-order models may be either linear or non-linear.

The project treats two important aspects of validation. The first is the focus on pre-test planning, i.e. the planning of the test such that test data (when that becomes available) is informative with respect to the physical properties that need to be validated. The second aspect is on the model calibration in itself. Model calibration can be seen as an optimization problem in which one searches for the model that gives a minimal deviation from test observations. However, it has been found that the selection of a proper formulation of the criterion function for such deviation is far from trivial. Various formulations that may suite the wind turbine application will be evaluated. Also, within the time-frame of the project, it is believed that real test data becomes available and model calibrations can be made. A collection of lessons learned from this (and from other sources) will be summarized to help future structural dynamics modellers to set up better models at first hand.

Results

A strong focus has been put on the development of model reduction and model validation methods. The work has been made in preparation for an (initially planned) large scale calibration following vibrational testing of blades for an off-shore wind turbine. The test did not materialise, because of the shift of focus at GE Wind as a reaction to disappearing business opportunities in the volatile off-shore wind turbine market. That shift of focus appeared very early during the project. However, the method development has been advancing and is now in a good position for real large scale calibration and validation. The work has resulted in papers as listed in a section below.

Fulfilment of SWPTC's goals

This project has contributed to the research aimed at achieving optimal wind turbines. Outcome of this project has been incorporated in an MSc course entitled Structural Dynamics – Model Validation, thus MSc students are learnt theory and obtained skills useful in wind power engineering. The project has contributed to the scientific output of the Centre in form of scientific papers.

Deviations from project plan

No major deviation from plan can be reported. The cooperation between the industrial partner and the university that started with strong intensity when GE Wind Energy had a local office in Karlstad, was terminated prematurely.

Publications

1. M. Khorsand Vakilzadeh, S. Rahrovani, and T. Abrahamsson, *An improved modal approach for model reduction based on input-output relation*, Proceedings of ISMA2012-USD2012, Leuven, pp 3451-3459, 2012
2. M. Khorsand Vakilzadeh, S. Rahrovani, and T. Abrahamsson, *Modal Reduction Based on Accurate Input-Output Relation Preservation*, Proceedings of IMAC XXXI, Garden Grove, California USA, 2013
3. J. Norlin, and C. Järpner, *Fluid Structure Interaction on Wind Turbine Blades*, MSc thesis 2012:24, Applied Mechanics, Chalmers University of Technology, 2012
4. M. Khorsand, A.T. Johansson, C.-J.Lindholm, J. Hedlund, T. Abrahamsson, *Comparison of Model Reduction Techniques of an NREL 5MW Offshore Wind Turbine Blade*, Proceedings of IMAC XXXII, Orlando, Florida, USA, 2014
5. M. Khorsand Vakilzadeh, A.T. Johansson, C-J. Lindholm, J. Hedlund, T. Abrahamsson, *Development of simplified models for wind turbine blades with application to NREL 5MW offshore research wind turbine*, presented at IMAC XXXII, Orlando, Florida, USA, 3-6 February, 2014
6. M. Khorsand Vakilzadeh, A.T. Johansson, T. Abrahamsson, *Bayesian Finite Element model calibration using manifold based Metropolis adjusted Langevin dynamics*, Proceedings of IX International Conference on Structural Dynamics, Porto, Portugal, June 30-July 02, 2014
7. M. Khorsand Vakilzadeh, *Calibration and Reduction of Large-Scale Dynamic Models - Application to Wind Turbine Blades*, Licentiate Thesis, Chalmers University of Technology, 2013

Submitted

1. M. Khorsand Vakilzadeh, V. Yaghoubi, A.T. Johansson, T. Abrahamsson, *Towards an autonomous modal parameter estimation framework: Mode clustering*, to appear in IMAC XXXIII, Florida, USA, 2015
2. V. Yaghoubi, M. Khorsand Vakilzadeh, T. Abrahamsson, A parallel solution method for structural dynamics response analysis, to appear in IMAC XXXIII, Florida, USA, 2015

As in-kind contribution from the university also:

1. M. Khorsand Vakilzadeh, V. Yaghoubi, T. Abrahamsson et al., *Manifold Metropolis adjusted Langevin algorithm for high-dimensional Bayesian FE*, Proceedings of the 9th International Conference on Structural Dynamics, 2014
2. S. Rahrovani, M. Khorsand Vakilzadeh, T. Abrahamsson, *A Metric for Modal Truncation in Model Reduction Problems Part 1: Performance and Error Analysis*, Conference Proceedings of the Society for Experimental Mechanics Series - Topics in Modal Analysis, 2014
3. S. Rahrovani, M. Khorsand Vakilzadeh, T. Abrahamsson, *A Metric for Modal Truncation in Model Reduction Problems Part 2: Extension to Systems with High-Dimensional Input Space*, Conference Proceedings of the Society for Experimental Mechanics Series - Topics in Modal Analysis, 2014
4. S. Rahrovani, M. Khorsand Vakilzadeh, T. Abrahamsson, *Modal Dominancy Analysis Based on Modal Contribution to Frequency Response Function* $\mathcal{H}_2$*-Norm*. Mechanical Systems and Signal Processing, 2014

5. M. Gibanica, A.T. Johansson, S. Rahrovani, et al., *Spread in Modal Data Obtained From Wind Turbine Blade Testing*, Topics in Experimental Dynamic Substructuring, Volume 2, Proceedings of the 31st IMAC - A Conference on Structural Dynamics, 2013
6. A.T. Johansson, C-J. Lindholm, M. Khorsand Vakilzadeh, et al., *Modeling and Calibration of Small-scale Wind Turbine Blade*, Topics in Experimental Dynamic Substructuring, Volume 2, Proceedings of the 31st IMAC - A Conference on Structural Dynamics, 2013
7. S. Rahrovani, M. Khorsand Vakilzadeh, T. Abrahamsson, *On Grammian-based reduction methods for moderate size systems*, 19th International Congress on Sound and Vibration, 2012
8. V. Yaghoubi, M. Khorsand Vakilzadeh, T. Abrahamsson, *Application of an automated modal analysis based on frequency response function estimates*, International Conference on Noise and Vibration Engineering (ISMA), 2012

External activities

The PhD student has participated in a 4-week course named *Advanced modeling and simulation techniques of (non)linear dynamic systems* at Vrije Universiteit Brussel (Belgium). He has been on a one month's visit to the research group of Prof. Scott Cogan at the University of Franche-Comté (France). He has also been participating in a one-week course named *Uncertainty and sensitivity analysis of numerical models* at Technical University of Denmark.

Project title	Evaluation of manufacturing methods and material selection for cost optimal rotor blades
Project number	TG4-2
Organisation	Chalmers University of Technology, Applied Mechanics
Project leader	Thomas Abrahamsson
Other participants	Anders T. Johansson (Postdoc)
Report for	2011-11-01 - 2014-09-30
Participating companies	DIAB, Marström Composite AB

Project description

A study made at the Linnaeus University in Kalmar on a request by Marström Composite AB shows that a significant reduction in rotor blade weight can be achieved when the design is swapped from a glass fibre composite design into a carbon fibre design with an autoclave manufacturing technique. In a comparison made against the most light-weight glass fibre blade on market, a reduction of about 11 metric tonnes, from 17.7 tonnes to 7 tonnes, was achieved for a 61.5 m long blade. Although we believe that a carbon fibre blade will be pricier than glass fibre blades, except for the most extreme MW wind turbines, we assume that the life cycle cost of the entire turbine system with such blades will be lower, resulting in less cost per produced electric energy. The reason for this is the exceptionally good fatigue strength of the autoclave hardened carbon fibre composite and its low weight that alleviate the gravity load on wind turbine components such as bearings, nacelle, yaw control system and turbine tower. Further use of stiffening polymeric foam may bring down the blade weight even further. That is by reducing the need for stiffening internal spars, ribs and load carrying hollow beams. Polymeric foam may also be added to the composite skin to increase the load carrying capability of the blade by eliminating buckling.

The industrial partners of this project have several interesting concepts, such as DIAB Core InfusionTM, prepreg without autoclave and prepreg with autoclave, for wind turbine blade design. These concepts are developed to suit their best design practice experience and production infrastructure. Amongst the components in a complete wind turbine, their expertise is presently focused on blade design, which is assumed to give the greatest cost reduction potential. In the wind turbine system, the blades are important components that affect the remaining structural components by heavy loading. Most of that loading is from wind and weight. To do a relevant life cycle cost analysis of the wind turbine system, and use the full potential of the reduced blade weight, a coupled system analysis and system optimization is required. The academic partner will do system modelling, simulation and optimization to substantiate cost reduction claims.

Results

A finite element based study of composite wind turbine blade modelling has been made in collaboration with Composites Consulting Group (CCG). An investigation of methods for wind turbine system modelling has been made with the support of Teknikgruppen AB. A detailed model of the NREL 5MW virtual test bed wind turbine blade has been developed in collaboration with CCG Composites and the parallel project TG4-1. Model reduction techniques designed to allow more direct coupling between high-quality blade models and reduced-order models for aeroelastic simulations have been investigated in collaboration with the sister project TG4-1. Synergy has been obtained from a parallel project (involving the project partner Marström Composites and the consultancy company Scandinavian Wind) that aims at developing and install new blades for Chalmers experimental wind turbine at Hönö. The manufacturing of the new blades to the Hönö 50kW machine has recently started. A measurement series will commence shortly. Studies of the Brazier effect, a nonlinear effect which causes conservative material selection for the core material towards the root section of many commercial blades, have been performed together with CCG. This work consisted partly of simulation work using the NREL model previously developed in the project and partly of experiments on representative scale models tested at DIAB's laboratory in Laholm. The above activities are aimed to support the development of an optimisation tool for wind turbine system design.

Fulfilment of SWPTC's goals

This project has contributed to the research aimed at achieving optimal wind turbines. It has contributed by a step that hopefully eventually will lead to that new material will be used in the blade design which can give a weight reduction of 60 % of the blades. By supporting and supervising MSc students in wind turbine blade testing and validation, high-quality training of students to expertise in wind power engineering has been provided. The project has contributed to the scientific output of the Centre in form of conference papers.

Deviations from project plan

According to the project plan of the project proposal the project should start in Q3 2011. The project was instead started in Q2 2012. The revised time plan wss followed.

Publications

1. A. T. Johansson, C-J. Lindholm, M. Khorsand Vakilzadeh, and T. Abrahamsson, *Modeling and calibration of small-scale wind turbine blade*, Topics in Experimental Dynamic Substructuring, Volume 2, Proceedings of the 31st IMAC, A Conference on Structural Dynamics, 2013, 2 ISBN/ISSN: 978-1-4614-6539-3
2. M. Khorsand, A.T. Johansson, C.-J.Lindholm, J. Hedlund, T. Abrahamsson, *Comparison of Model Reduction Techniques of an NREL 5MW Offshore Wind Turbine Blade*, Proceedings of IMAC XXXII, Orlando, Florida, USA, 2014
3. A.T. Johansson, C.-J. Lindholm, J. Hedlund and T. Abrahamsson, *Development of simplified models for wind turbine blades with application to NREL 5MW offshore research wind turbine*, Proceedings of IMAC XXXII, Orlando, Florida, USA, 2014
4. I. Echaniz, C. Ekberg, M. Josefsson, M. Ljungberg, J. Wass, *FE-modelling and testing of sandwich composites*, Project Report, Applied Mechanics programme, Chalmers 2014
5. I. Fransen, K-J. Larsson, J-A. Lindhult, M. Gonera, A. Suryanarayana, E. Eliasson, *FE-modelling of wind turbine blade*, Project Report, Applied Mechanics programme, Chalmers 2014
6. T. Jungbark, *Power regulation of a vertical axis wind turbine*, MSc Thesis, 2014

Submitted

- C-J. Lindholm, A.T. Johansson, J. Hedlund, *Experimental analysis of stresses in sandwich structures due to the Brazier effect*, submitted to ICCM20 2015

As in-kind contribution from the university also:

1. A. T. Johansson, A. Linderholt, Y. Chen and T. Abrahamsson, *Model Calibration and Uncertainty Quantification of A600 Blades*, submitted to IMAC XXXII, Orlando, Florida, USA, 2014
2. M. Gibanica, A. T. Johansson, A. Liljerehn, P. Sjövall and T. Abrahamsson, *Experimental-analytical Dynamic Substructuring of Ampair Testbed: A State-Space Approach*, submitted to IMAC XXXII, Orlando, Florida, USA, 2014
3. Dynamics of an offshore-based vertical axis wind turbine, Project Report, Applied Mechanics programme, Chalmers 2013

External activities

Work on the small-scale wind turbine model has continued, both in terms of blade modelling and in assembling blade models to the hub using substructuring methods. Full system measurements and comparisons with similar systems set up at the Linneaus University in Växjö and the Technical University of Stuttgart have also been investigated. Dr Anders Johansson has also at two occasions been visiting the prominent research group working with model calibration under Prof. Scott Cogan at the University of Franche-Comté. Dr Johansson has furthermore supervised two project course projects studying the geometrically nonlinear effects of large-scale wind turbine blades in collaboration with the project partner DIAB. A master thesis on development of vertical axis wind turbines, resulting in a scale prototype tested in a wind tunnel at Volvo Trucks, was also supervised by Dr Johansson. The above-mentioned parallel project to develop the experimental turbine at Hönö has been furthered to the point of blade manufacturing.

Project title	Load and Risk Based Maintenance Management of Wind Turbines
Project number	TG5-1
Organisation	Chalmers University of Technology, Electric Power Engineering
Project leader	Lina Bertling Tjernberg, Chalmers/KTH (up til May 2014) / Ola Carlson, Chalmers
Other participants	Pramod Bangalore (PhD student)
Report for	2011-04-01 - 2014-09-30
Participating companies	SKF, Göteborg Energi, Triventus

Project description

This project aims to increase the availability of wind turbines, while reducing the overall costs of maintenance.

Below is a short summary of the project:

1. The main idea in the project is to use the abundant data available from the SCADA system of the wind turbine in order to estimate the health of critical components, and to make a focussed maintenance effort on those components, which are at a risk of failure.
2. An artificial neural network (ANN) model is created to use data stored in the SCADA system to estimate the health of the gearbox bearings.
3. An automated procedure to decide and update the training data set has been created; this enables to select individual training data sets for each wind turbine.
4. A statistical distance measure is used to analyse the signals from the ANN model, and to decide the threshold for anomalous operation.
5. Case studies have been performed to validate the ANN-based condition monitoring methodology.
6. A maintenance management framework–the Self-Evolving Maintenance Scheduler–has been proposed.
7. A mathematical model will be proposed to optimize the maintenance activities by using an opportunistic structure, based on the paper [1] shown below.

Results

A literature survey was carried out to investigate the state-of-the-art in condition based maintenance optimization and the use of SCADA data for condition monitoring of the wind turbine components. From the literature survey it was found that ANN could be used to effectively estimate the condition of some critical components in wind turbine.

A statistical analysis was performed on the maintenance reports for 28 onshore wind turbines rated 2 MW. The result from analysis of around 800 maintenance reports showed that the gearbox is a critical component in the wind turbine, which accounts for the longest downtime.

An ANN-based condition monitoring methodology was created; it uses the measurements stored in SCADA along with the SCADA alarms and warnings to estimate the health of the components being monitored. Figure 10 presents the output from the ANN-based condition monitoring system for a wind turbine, which had recorded a failure in the gearbox bearing. The SCADA warnings and alarms have been superimposed on the same time scale. It can be seen that the number of SCADA alarms and warnings have increased at about the same time as the signal has crossed the threshold, indicating a degradation in the bearing. The system was hence able to detect the fault in the gearbox bearing in advance, providing an opportunity to plan the replacement activity.

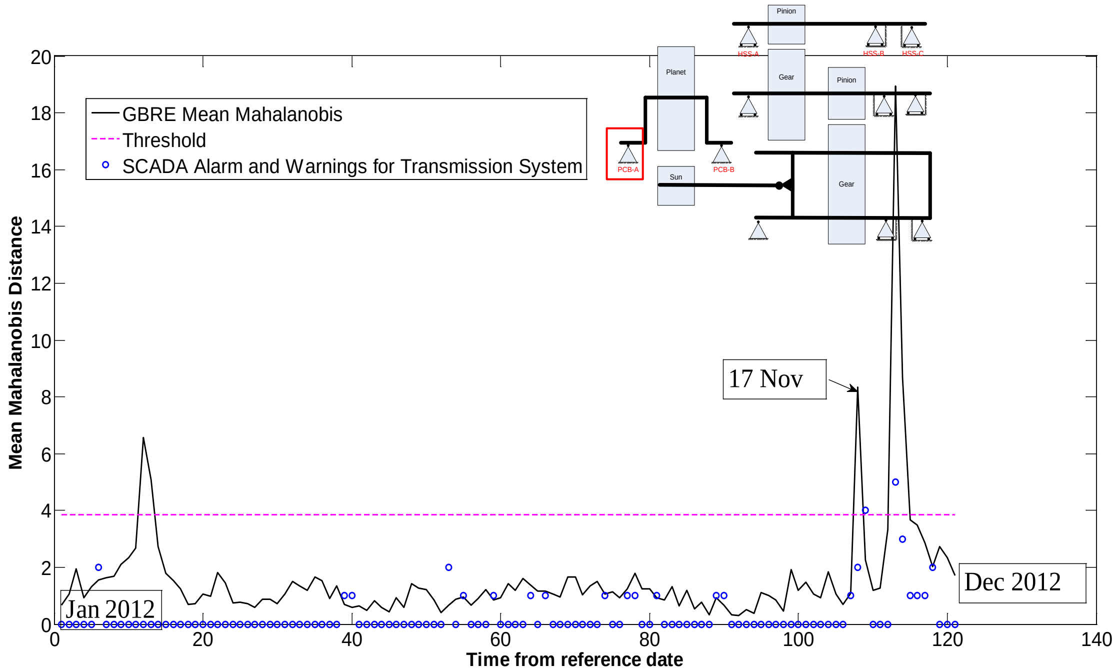


Figure 10: Output from the ANN-based condition monitoring system for a wind turbine with gearbox bearing fault

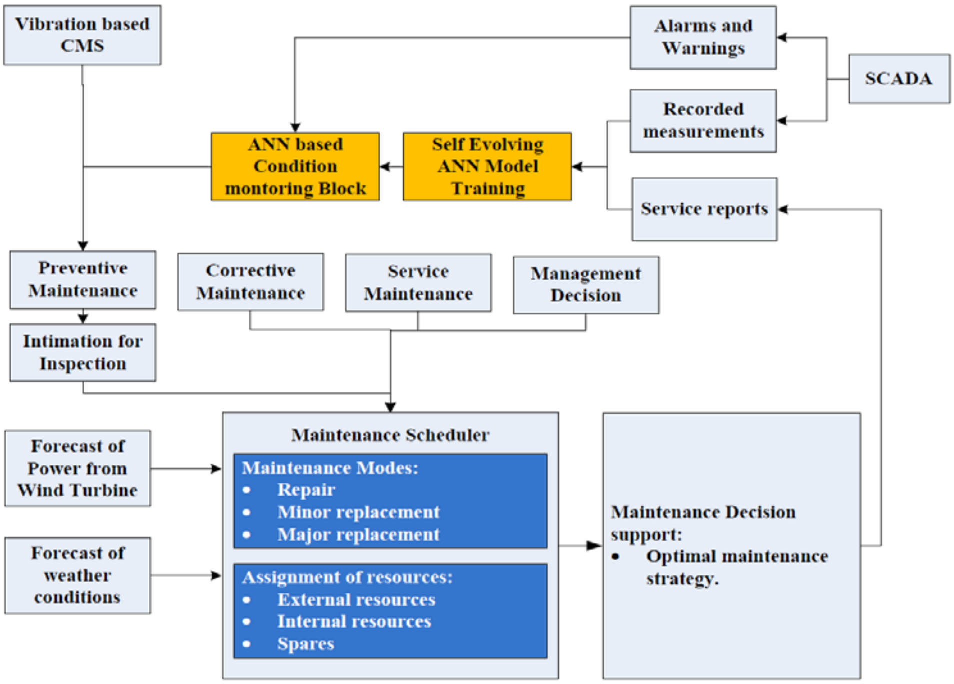


Figure 11 SEMS maintenance management framework

A maintenance management framework, referred to as SEMS (Self-Evolving Maintenance Scheduler), has been proposed, as shown in Figure 11. The SEMS framework incorporates the indication of failure from various CMS systems in order to plan maintenance activities. The SEMS framework will also take into consideration opportunities to perform maintenance on other components in order to optimize the overall maintenance cost.

A preliminary mathematical model has been proposed, which is based on the preventive maintenance scheduling problem with interval costs (PMSPIC) model [1], proposed by the mathematical optimization group at Chalmers. The model allows a multi-objective optimisation framework with opportunistic maintenance scheduling capability. The maintenance optimisation model aims at using condition monitoring system information in adapting the preventive maintenance schedule.

Fulfilment of SWPTC's goals

This project contributed towards SWPTC's goal of reducing the maintenance cost of wind turbines. The aim was to develop a maintenance strategy based on measured information about the conditions of the components, and the costs associated with performing maintenance. This will aid in accomplishing effective maintenance, lower downtimes and total lower costs, thanks to a careful planning.

Deviations from project plan

It was planned to use the vibration measurement data from the condition monitoring system. However, the necessary data was not available.

Publications

1. P. Bangalore and L. B. Tjernberg, *An approach for self evolving neural network based algorithm for fault prognosis in wind turbine*, in *PowerTech (POWERTECH), 2013 IEEE Grenoble*, 2013, pp. 1-6
2. P. Bangalore and L. B. Tjernberg, *Self-evolving neural network based algorithm for fault prognosis in wind turbines: A case study*, Probabilistic Methods Applied to Power Systems (PMAPS), Durham, 2014
3. P. Bangalore, *Load and Risk Based Maintenance Management of Wind Turbines*, Licentiate Thesis, Dept. of Energy and Environment, Chalmers University of Technology, Gothenburg, Sweden, 2014

Submitted

1. P. Bangalore and L. B. Tjernberg, *An Artificial Neural Network Approach for Early Fault detection of Gearbox Bearings*, submitted to IEEE Transactions on Smart Grids. (Awaiting reply)

External activities

- Participation in IEAwind - Task 33 'Reliability Data: Standardizing data collection for wind turbine reliability and O&M analyses'. The aim of the task is to develop standardized procedures for wind turbine maintenance and reliability data collection.
- Participation in Nordic Wind Operation and Maintenance (NWOM) meetings. The network aims at connecting researchers and industry in Nordic countries, working in the topic of operation and maintenance of wind power plants.
- Regular theme group meetings with project partners.
- SKF condition monitoring system training.

References

[1] E. Gustavsson, M. Patriksson, A. Strömberg, A. Wojciechowski, M. Önnheim, *Preventive maintenance scheduling of multi-component systems with interval costs*, Computers & Industrial Engineering, vol. 76, pp. 390-400, 2014.

Project title	Current damages in bearings – mechanisms for charging, discharging and damage control
Project number	TG5-2
Organisation	Chalmers University of Technology, High Voltage Engineering
Project leader	Jörgen Blennow
Other participants	Abhishek Joshi (PhD student)
Report for	2011-03-01 - 2014-09-30
Participating companies	ABB, Göteborg Energi, SKF, Triventus Service

Project description

The project formally started 2011-03-01 but the recruitment of the Ph.D.-student (Abhishek Joshi) took longer time than expected and his employment started 2011-11-07.

The mechanical bearing constitutes a key component for the reliability of a wind turbine. Understanding of how bearing damages arise and how they can be prevented is therefore of great importance. Failures of bearings in electrical machines caused by current damages started to increase during the 1990's after the introduction of high frequency switched converters based on IGBT (Insulated Gate Bipolar Transistor) technology. The high frequent voltage source in combination with capacitive parasitic elements charges the shaft and its corresponding capacitance. The energy is then discharged through the lubricating film in the bearing with mechanical wear as a result.

The aim with this project was to increase the knowledge of the mechanism behind current induced damages in wind power applications based on experimental work and modelling.

The original project plan laid out was very ambitious, and as it turned out, too ambitious and included the following tasks: 1) Literature review; 2) Modelling of parasitic elements; 3) Modelling of shaft voltage based on literature studies and if possible based on on-line measurements on wind turbines; 4) Overview inventory of bearing failures due to suspected bearing currents and if possible linking of damages to bearing currents; 5) Development of an equivalent circuit model suitable for simulation of bearing currents based on literature studies and parameter measurements; 6) development and construction of static experimental set-up for characterization of the static dielectric breakdown voltage and the mechanisms that are responsible for the insulation breakdown; 7) Design of and construction of a new experimental test rigor modification of the previous one for characterization of the electrical properties of the bearing during different operating conditions (e.g. dynamic and transient); 8) Improvement of the equivalent circuit model and further simulations; and, 9) Writing of thesis for the degree of Licentiate of Engineering. As it turned out, the characterization of what was happening in the bearing was found to be more complex and time consuming to investigate, analyse and understand than earlier expected.

In May 2013 it was therefore proposed by the project leader and decided by the board of SWPTC to narrow down the tasks and to entirely focus on studying the phenomena occurring in the bearing exposed to shaft voltages rather than analysing the entire electrical and mechanical drive system. The revised tasks was formulated as: A) Literature review; B) Experimental investigation and characterization of the current flowing through a bearing when exposed to a shaft voltage and elucidation of the responsible mechanisms; C) Electrical characterization of different commercially available lubricants; D) establishment of a model describing the phenomena occurring in a bearing that can be implemented in the following system analysis; E) Overview inventory of bearing failures due to suspected bearing currents; and, F) Writing of thesis for the degree of Licentiate of Engineering.

Results

The main scientific approach in the project was to propose an electrical circuit model of a bearing exposed to a shaft voltage according to Figure 12 where each electric circuit component describes an electro-physical property which was experimentally investigated. The switch represents the breakdown of the insulating properties of the lubricating film enabling a conductive path for the bearing current to flow. The switching pattern depends on mechanical load, rotational speed, shaft voltage magnitude and shape, lubricant, dielectric breakdown voltage of the lubricating film, pre-history of bearing current activity (i.e. a memory effect) etc. The resistance R_b represents the rather low resistance of the bearing during bearing current enabling the discharge of stray capacitances between the rotor of the machine and its surroundings. The parallel connection of the resistance R_L and the capacitance C_b represent the dielectric properties of the lubricant (conductivity, relative permittivity) and the geometry of the bearing (outer and inner raceway, rolling elements and film thickness). The model in Figure 12 is denoted “simplified” since it represents a first modelling attempt and it can easily be foreseen how it can be extended by also including dynamic properties.

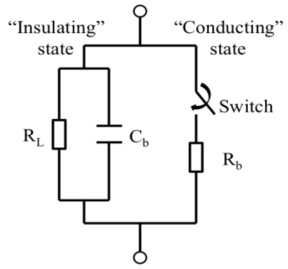


Figure 12: Proposed simplified electrical circuit model of a bearing exposed to a shaft voltage. The switch represents breakdown of the insulating properties of the lubricant thus enabling a conductive path for the bearing current to flow.

A typical measured discharge pattern, corresponding to a switching pattern of the switch in Figure 12, is shown in Figure 13.

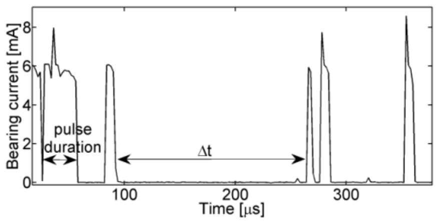


Figure 13 Measured typical bearing current pattern in a miniature test rig showing varying pulse duration and time between current pulses (measurements conducted under current limited conditions).

An example of bearing current activity observed when applying a rather low AC voltage is illustrated in Figure 14. The instantaneous voltage level when the current activity starts is in this case 2.1 V and when it stops 1.9 V. Observations at higher voltage levels have revealed significant memory effects.

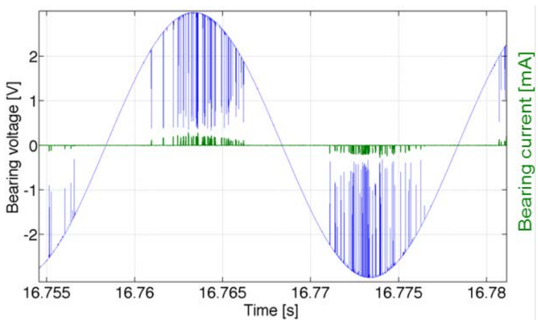


Figure 14: Measured bearing current trace and voltage across bearing in a miniature test rig showing inception of bearing currents at 2.1 V and extinction voltage of 1.9 V (measurements conducted under current limited conditions).

Since the electrical model includes four circuit elements that each depends on numerous physical, electrical and mechanical parameters the test matrix became extensive. For analysis of the recorded data (mainly measured voltage and current traces) Matlab code was developed and used. In addition statistical behaviour and memory effects have been observed making the analyses complicated.

Results from surface morphology analyses were performed on a roller bearing from a wind turbine replaced due to suspected bearing current activity are shown in Figure 15 (supplied by Triventus).

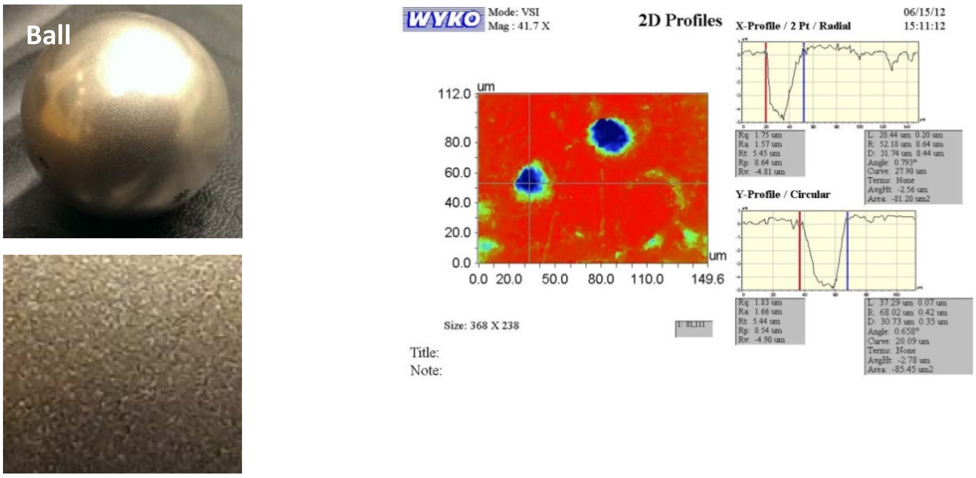


Figure 15: Morphology analysis of a replaced bearing damaged in operation shows 50 craters per mm^2, an average crater volume of 10^3 μm^3 and the depth varies from 5 to 20 µm.

The main achievements in the project are shortly:

Experiments on small scale and large scale test rigs
A small-scale test rig from SKF was used at Chalmers for experiments. The tests have been conducted as a function of operating points such as rotational speed, mechanical load, voltages of different amplitudes, frequencies and wave shapes (sine, saw-tooth and triangular). A ball bearing with grease lubrication was used as test object and an extension to liquid lubrication system has been discussed with SKF. The experimental results obtained from small scale test rig have been re-verified on a large scale test rig, which is made available at SKF. A spherical bearing with cylindrical and tapered bore and with controlled bath of liquid oil lubrication has been used as test object.

Development of computer code for analyses of bearing current activity under alternating voltages
An offline data analyses code has been developed on Matlab platform to quantify bearing current activity for DC and alternating shaft voltages. The code is able to identify inception and extinction voltages of bearing current activity along with current pulse duration and frequency of breakdown for recorded experimental data. The Matlab code reports statistical measured mean value of inception and extinction voltages, along with standard deviation, and can be selected by user.

Bearing capacitance calculations
Bearing capacitance has been calculated for small and large scale bearings as a function of different rotational speed and mechanical load on the bearing. The results show a decrease in bearing capacitance with an increase in rotational speed of the bearing. An increase in mechanical load on the bearing did not significantly affect the calculated bearing capacitance. The results have been re-verified using AWIS technique (Arbitrary Waveform Impedance Spectroscopy) developed in an ongoing Elektra/Energimyndigheten financed project at Chalmers.

Characterization of electrical breakdown of the rotating bearing
Previous investigations from small scale bearing, under DC voltages have revealed that the breakdown frequency increases with increasing voltage, decreasing rotational speed and increased mechanical load. The effect of increasing DC voltage has also been re-verified on large test bearing, and results are reproducible. The investigation has been further expanded to include the effect of different types of alternating voltages, tested at fixed operating conditions. The results reveal that with increasing amplitude of applied voltage across the bearing (up to 10 V_{peak}), the inception voltage for bearing current activity increases until a critical voltage level is reached. After reaching critical voltage level, the mean inception voltage for bearing current activity reduces with an increase in applied voltage. An increase in frequency of the applied voltage from 50 Hz to 2 kHz results in reduction of mean inception voltage of bearing current activity. At a given frequency, the mean inception voltage for bearing current activity is also recorded highest for triangular wave shape, followed by saw-tooth

and sine voltage wave shape. With an increasing amplitude of applied voltage across the bearing, the duration of current pulses increases, with a decrease in time interval between successive pulses. The measurements suggest that the threshold voltage for breakdown of the lubricating film is very low – in the order of a few volts for the small bearing tested. The results from the tests on small scale test bearing are re-verified on large scale test bearing, and show that experimental based electrical modelling characteristics of switching characteristics of bearing are up-scalable from small ball bearing to a large spherical bearing. In the near future the investigation will be extended to also include variable discharge energy. Additional tests are planned to re-do tests with liquid lubricant instead of grease lubricant in the miniature ball bearing with the help of minor modifications in the near future.

Electrical characterization of lubricants
Different lubricants have been received from SKF and Triventus for relevant electrical characterization. Dielectric response measurements in the frequency domain as a function of increasing temperature and breakdown tests for short gaps of 100 µm and 200 µm have been conducted for these bearing lubricants. The relative permittivity of lubricating oil was found to be in the range 2.1-2.3 at 40 Hz and 50 °C and for grease between 3.8 and 4.7. At very low frequencies, 0.1-10 mHz polarization effects of the highly viscous grease increased the relative permittivity significantly. The conductivity for an additive free lubricant was 2.9 pS/m and increased to 7.6 pS/m after use. For a fresh oil with additives the conductivity was 114 pS/m and for fresh grease 4200 pS/m which after use decreased to 2450 pS/m. The breakdown field strength for a short gap, 100 µm, was for fresh oil without additives 24.4 kV/mm and after run-in 16.5 kV/mmm and for fresh oil with additives 30.8 kV/mm.

Surface analyses of bearing balls being damaged during operation
Triventus has supplied six sets of drive end and non-drive end bearings being damaged during operation in wind turbines. Surface analyses have being conducted by Prof. Nyborg and Dr. Tam at the Surface and Microstructure Engineering group at Chalmers on the eight balls in one of the bearings. Both low power magnification (2.2x) and high power magnification (40x) were employed for measurements of surface roughness and characterization of crater geometry respectively. For the micron level roughness the vertical scanning interferometry mode was chosen. The diameter of the balls was 41.3 mm. Craters were found evenly distributed over the ball surface. A density of approximately 50 craters/mm^2 and an individual crater volume around 1000 μm^3 were found. The findings have not yet been correlated with operational data of the wind turbine such as operational time, loading, vibrations etc.

Fulfilment of SWPTC's goals
This project contributes to fulfilment of several of the Centre's goal. A better understanding of bearing currents, their detrimental effect and thus how they can be mitigated will reduce maintenance cost for exchange of damaged bearings and thus contribute to a longer lifetime of the turbine. When increasing power electronic components in the system in order to reduce weight it is important to consider effects on bearing currents. The project also contributes to research of the highest class through state-of-the-art study of fundamental aspects of a mechanical bearing considered as an electrical component as a part of an electrical circuit. In addition, it also contribute to the engineering education since these phenomena is relevant to use as application examples in the subject of high voltage engineering.

Deviations from project plan
A mentioned above the original project plan was revised in May 2013 and the tasks narrowed down to entirely focus on studying the phenomena occurring in the bearing under exposure to shaft voltages rather than analysing the entire system. Two deviations from the revised project plan (May 2013) should be noted.

The first deviation is Task E "Overview inventory of bearing failures due to suspected bearing currents. The results should be included in a paper". The main reason that this not has been done is that the measurements on the test rigs and elaboration of the software needed for analyses of the collected data has been considerably more time consuming than expected. This task is however very important and has therefore been included as task 5 in the proposal continuation of the project towards doctoral degree in SWPTC stage 2.

The second deviation is that according to the project plan and the plan for the Ph.D. student, the student should have obtained his Licentiate Degree by May 2014. The student is approximately seven months delayed. The main reasons for this is that this project opened up a new field of research at Chalmers, the experimental character of the project and that in the beginning was difficult to obtain reproducible results due to memory effects and the time consuming development of Matlab data analyses code for analysis of the collected data. A first draft of the thesis is available as well as the first draft for two new papers that reports work conducted. Realistically the thesis can be presented at the end of January 2015.

Publications

1. A. Joshi, J. Blennow, *Investigation of the Static Breakdown Voltage of the Lubricating Film in a Mechanical Ball Bearing*, Nordic Insulation Symposium (Nord-IS 13), Trondheim, Norway, June 9th - 12th, 2013.

Submitted

1. A. Joshi, J. Blennow, *Electrical Characterization of Bearing Lubricants*, Conference on Electrical Insulation and Dielectric Phenomenon (CEIDP 2014), Des Moines, Iowa, U.S.A October 19th – 23rd, 2014.

Publications being prepared

1. Jörgen Blennow, Abhishek Joshi, “Current induced bearing damages in wind power applications – an attempt to understand and electrically model bearing current activity” abstract accepted, Conference for Wind Power Drives, CWD2015, Aachen 3rd – 4th March 2015.
2. Journal paper draft: Abhishek Joshi, Jörgen Blennow, “Electrical Modeling of Mechanical Bearing”
3. Journal paper draft: Abhishek Joshi, Jörgen Blennow, “Investigation of the Static Breakdown Voltage of the Lubricating Film in a Cylindrical Rolling Element Bearing”-
4. Journal paper draft: Abhishek Joshi, Jörgen Blennow, “Current Conduction Characteristics of a Spherical Rolling Element Bearing under Basic Alternating Wave Shapes”
5. Thesis draft for the degree of licentiate of engineering: Abhishek Joshi, *Elaborating Electrical Properties of Mechanical Bearing through Experiments*.

External activities

- Poster and project presentation at Vindkraftsforskning i fokus 2012, Gothenburg, January 18-19, 2012.
- Poster and project presentation at Wind Power Research in Focus 2013, Gothenburg, September 16-17, 2013.
- Poster presentation at ABB PhD Days, Ludvika, September 23-24, 2013.
- Poster presentation at ABB PhD Days, Västerås, September 23-24, 2014.
- Poster presentation at CEIDP 2014, Des Moines, Iowa, U.S.A, October 19-23, 2014.
- Jörgen Blennow was invited to take part in a failure analysis meeting at Preem Raff in Lysekil in September 2014, where bearing activities were suspected as the root cause of failure.

Project title	Sensors for ice detection on wind turbine rotor blades
Project number	TG6-1
Organisation	Chalmers University of Technology, Dynamics
Project leader	Viktor Berbyuk
Other participants	Jan Möller, Bo Peterson, Stellan Wickström, Lena Klasén, Håkan Johansson, Olle Bankeström
Report for	2012-09-01 – 2014-09-30
Participating companies	WindVector AB, DIAB, SKF

Project description

The scope for this project was to provide theoretical background, experimental systems, algorithms and methods to detect ice build-up on rotor blades on wind turbines. The long term goal of the project is to transfer knowledge of the potential of the sensor concepts to the industry, to be used for cost effectiveness of the two sensors. The main objectives of the project was to design two prototypes of sensor systems and to evaluate them in Cold Climate Laboratory with respect to their applicability to be used for early ice detection on rotor blades of wind turbines. These two prototypes are:

- Ice detection system based on controlled acoustic waves & magnetostrictive actuators (Chalmers)
- Ice detection system based on LIDAR sensor (WindVector AB).

In the extension of this project it was planned to instrument a new experimental set up with the test objects based on rotor blade Vestas V47.

Results

The project provided a demonstrator for the ice detection system based on controlled acoustic waves, magnetostrictive actuator and accelerometers. An experimental set-up with the demonstrator in cold climate lab (CCL), composite test object and equipment for glaze and rime ice production have been developed (see Figure 16 – Cold Climate Lab and Experimental Set-up; Figure 17 – Equipment for ice manufacture). The composite material in the test object was the same as normally used in wind turbine blades. LabVIEW and DAQ system from National Instruments were used for measurement data gathering and processing. The propagation of three orthogonally polarized acoustic waves was studied for different scenarios of icing of the test object. Data was measured by means of 6 accelerometers positioned, 3 each, in 2 holders at approximately 0.4 m from each end of the 8 m long test object. A number of indicators were proposed and numerical algorithm has been developed to analyse the measurement data. The obtained results showed that the formation of ice, the ice mass, icing areas and the temperature have a significant influence on guided wave propagation w.r.t. Fourier transform, amplitude attenuation and RMS values as indicators. It was also shown that there is no significant damping in the material that has been tested concluding that the proposed ice detection system based on controlled acoustic waves is a promising approach for ice detection. Details of the results obtained have been presented at International Conference SPIE2014, Smart Structures/NDE, San Diego, USA, and published in [1].

The project also provided a demonstrator for the laser based sensor for ice detection (Figure 18 – LIDAR sensor for ice detection). Here the first phase of the work included specification of the experimental sensor set-up, LIDAR system assembly and design of the experiments. The cold climate chamber enabled measurements with the LIDAR system under conditions that allowed for comparison of how well the LIDAR system was suited for ice detection. The spectral properties of uncovered rotor blades have been studied in comparison to ice and snow build-up on the rotor blades, to detect anomalies indicating ice accretions. For water, the signal level does not decrease to a minimum as the water drops only partially cover the test object causing the received signal to be a mix of the “normal” signal level of the test target and the decreased signal level caused by the water drops on the test target. The same principle holds for ice accretion, that the signal level decreases gradually as the ice is built-up on the test target. As the ice layer gets thicker, the signal level reaches a minimum for ice layers of only a few mm. The LIDAR system and the anomaly based detection algorithm shows that the data can be used for early detection of ice and water. Part of the results obtained has published in [2].

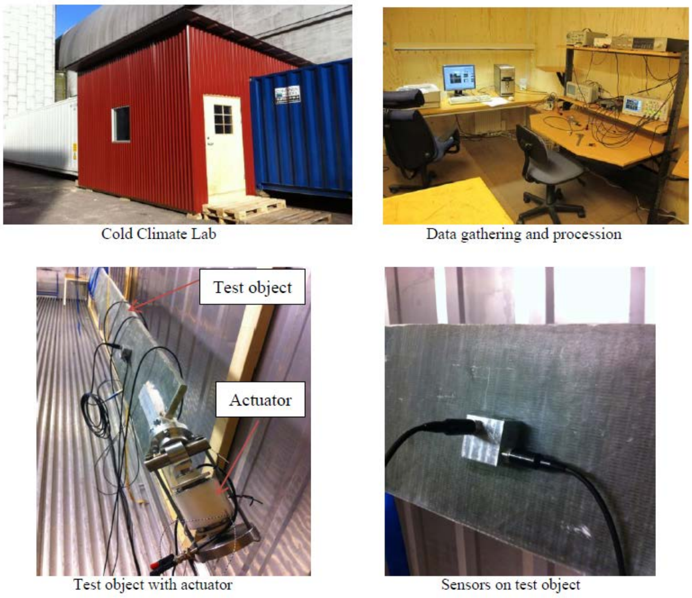


Figure 16: Cold Climate Lab and Experimental Set-up

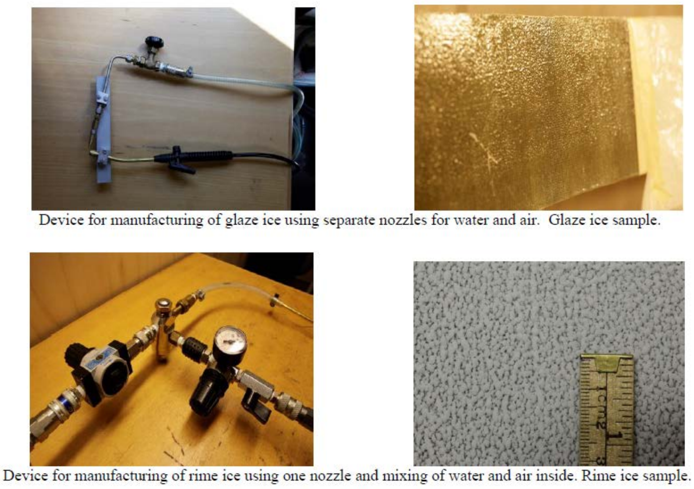


Figure 17: Equipment for ice manufacture

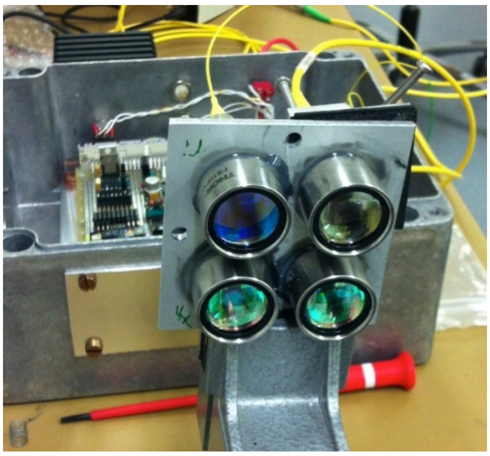


Figure 18: LIDAR sensor for ice detection

During the extension of the project the specifications for the test object to be used in experimental set up in Cold Climate Lab based on rotor blade of Vestas V47 have been developed and the analysis of available actuation and sensing transducers to be chosen for a new experimental set has been done. The test object, used rotor blade of Vestas V47, was received at the end of September 2014 from Connected Wind Services (Figure 19).

Figure 19: Vestas V47 blade at the Chalmers Cold Climate Lab

Fulfilment of SWPTC's goals

The results of the proposed project can be used to increase efficiency of de-icing systems of wind turbines in cold climate and in this way can significantly contribute to wind power system performance optimisation. Research on developing ice detection sensor technologies with application to wind turbine will support and accelerate moving wind power technology to cold climate. It will make possible to increase wind energy production, increase production of wind turbines and their components, like rotor blades, novel condition monitoring systems, others. The obtained results are used in engineering education and were published as internationally recognisable scientific papers.

Deviations from project plan

Due to late delivering of the Vestas V47 blade the work on instrumentation of the new test object and design of the new experimental set up in Cold Climate Lab have been delayed.

Publications

1. V. Berbyuk, B. Peterson, J. Möller, *Towards early ice detection on wind turbine blades using acoustic waves", Proc. of SPIE, Nondestructive Characterization for Composite Materials*, Aerospace Engineering, Civil Infrastructure, and Homeland Security 2014, San Diego, California, USA, March 09, 2014, 9063 pp. 90630F-1 - 90630F-11
2. L. Klasén, *Lidar Systems for Wind Energy Applications*, Proceeding of Swedish Society of Automated Image Analysis (SSBA) Symposium on Image Analysis, 2014

External activities

A new PhD project was granted by Swedish Energy Agency for the period of September 2013-December 2016. The project is running with PhD student employed at Chalmers from December 2013 in cooperation with Chalmers Industriteknik and WindVector AB. This project is considered as continuation of the work performed within the TG6-1 project.

Project title	Efficiency and influence of heating device on wind turbine blades
Project number	TG6-2
Organisation	Luleå University of Technology, Mechanics of Solid Materials
Project leader	Jan-Olov Aidanpää
Other participants	LTU, Swerea SICOMP, Chalmers
Report for	2013-01-01 – 2014-09-30.
Participating companies	Vattenfall, Skellefteå Kraft, DNV KEMA, H Gedda Consulting, Bollebygds Plast.

Project description

The aim of the project was to develop models and experimental methods to evaluate the efficiency of deicing equipment and its influence on the expected life of the turbine blades. In addition, new technologies for ice detection have also been evaluated. Experiments have mainly been performed in climate room at LTU but also on full scale wind turbines. The target was to understand and in future increase the efficiency of wind turbines in cold climate under icing conditions. It was early decided that the focus of the study should be on electrically heated carbon fibres in the laminates which is frequently used in wind power blades subjected to icing conditions. At Skellefteå Kraft, a thermal evaluation technique was developed by use of a mini helicopter equipped with thermal camera. With this new technique they can evaluate the functionality of the heating system before the winter and thereby increase the availability. At Sicomp the degradation of composite laminates has been evaluated due to heating device incorporated on the leading edge on the blade. The results indicate that degradation should not be a problem if the heating device works properly. At the end of the project time it was concluded that some more experiments were needed to verify the simulation models. An extension of the project was approved until the end of December 2014.

The project was mainly be performed by one senior at LTU and one senior at Swerea SICOMP. Chalmers will contribute with the knowledge on modelling and evaluation of available as well as novel developed sensor technologies for ice detection. The industrial partner Skellefteå Kraft will plan and perform the measurements at the wind power unit together with the research partners. Vattenfall have a long experience of wind power in cold climate and is performing own projects in this area. Vattenfall has contributed with experience and participate in planning of the whole project. H Gedda consulting has long experience from deicing equipment and assisted in the planning and evaluation of the measurements. Bollebygds Plast contributed with laminates of own design which was evaluated in cold laboratory at LTU.

In this project, experimental techniques have been developed at university and on real wind power turbines. At LTU analytical modelling and FEM was used to develop tools for simulating the deicing process which has been evaluated both in lab and on real turbines. At Swerea test laminates was manufactured and modelling of degradation of material due to heat has been developed. At Chalmers the knowledge gained within the running SWPTC TG6-1 project “Sensors for ice detection on wind turbine rotor blades” was used to study the possibilities to increase efficiency of de-icing system due to available sensors for early ice-detection.

In the project lab-tests was used to develop techniques for modelling and measurements. The analytical modelling consists of heat transfer modelling of heated laminate with ice and degradation of the laminate due to heat.

The project was directed by steering group meetings each quarter consisting of all the partners. The main task of the steering group is to direct the research into questions of industrial interest and to follow up the planned activities. An important task for the steering group is also to facilitate the full scale measurements on real wind turbines.

Results

The project was initiated in 2 January and the kick off meeting was in Skellefteå 21-22/2. Other project meetings have been held three times a year at Vattenfall, Skellefteå Kraft and LTU. A one day symposium was given in Luleå 19/3 2013 on “Ice detection and de/anti-icing systems”, The project has also been presented at the conference " Wind power research in focus" Gothenburg 16-17th of September 2013 and at project meetings. During 2014 the project time and budget was changed to an ending in September 2014. But since the measurements from Uljabuouda weren't satisfactory the project therefore applied for an extension which was accepted. Therefore the original plan is valid again.

In the project there is an aim to get thermal measurements on a real wind turbine the deicing process. To do the measurements a mini helicopter with thermal camera was selected early. The idea was to inspect the blades with the camera during the deicing process. It was however not so easy to control the helicopter and no successful measurement were completed until end of September 2014. In Figure 20 the measurement technique is shown.

Figure 20: Measurements from Uljabuouda with mini helicopter

From these measurements qualitative results could be compared with the developed simulation models. The results from these measurements will be used to calibrate the model for blades without ice.

In the project, two sets of test plates have been manufactured at Sicomp and one set of test plates at Bollebygds Plast. A detailed description of the manufacturing of the test plates at Sicomp is found in [1]. The laminate was selected to be as close as possible to a real wind power blade but in form of a flat plate with the size 1x0.5m. Bollebygds Plast used own technique to manufacture a similar plate. From the experience of the first test plates and knowledge from Bollebygds Plast, the thermal properties of the second set of test plates were significantly improved.

Test in the freeze room was developed in the project. The best method to study the deicing process was to build up a rectangular ice block on the plate and measure temperatures on a vertical plate. Due to gravity the ice block starts to slide when the interface ice layer was melted. Simulation models were evaluated and a criteria for the initial slide was found. In Figure 21 the setup in the climate room is shown.

Figure 21: Set up in the climate room for deicing experiments.

This criterion for deicing is conservative in the sense that it provides a maximum time for the deicing process on real blades. On a real wind turbine several other loads for example vibrations and centrifugal acceleration will cause an earlier loss of ice. However, the developed criteria will give an estimate for how long time it will take. More tests will be performed in November to analyse the validity of the criteria for different ice loads.

A simulation models was developed in an in-house one dimensional FEM code. An own code was selected in order to better control the change of parameters during the deicing process. In Figure 22 the model is shown.

Figure 22: Model of the plate with ice. From left gray is glass fibre laminate, red is core material, gray glass fibre, black carbon fibre, gray gelcoated surface and blue ice.

In the modelling of the ice the thermal properties changes when ice is transformed into water. For each finite element the absorbed energy is needed to be measured in order to find the timing of this phase change. In Figure 23 a typical simulation is shown.

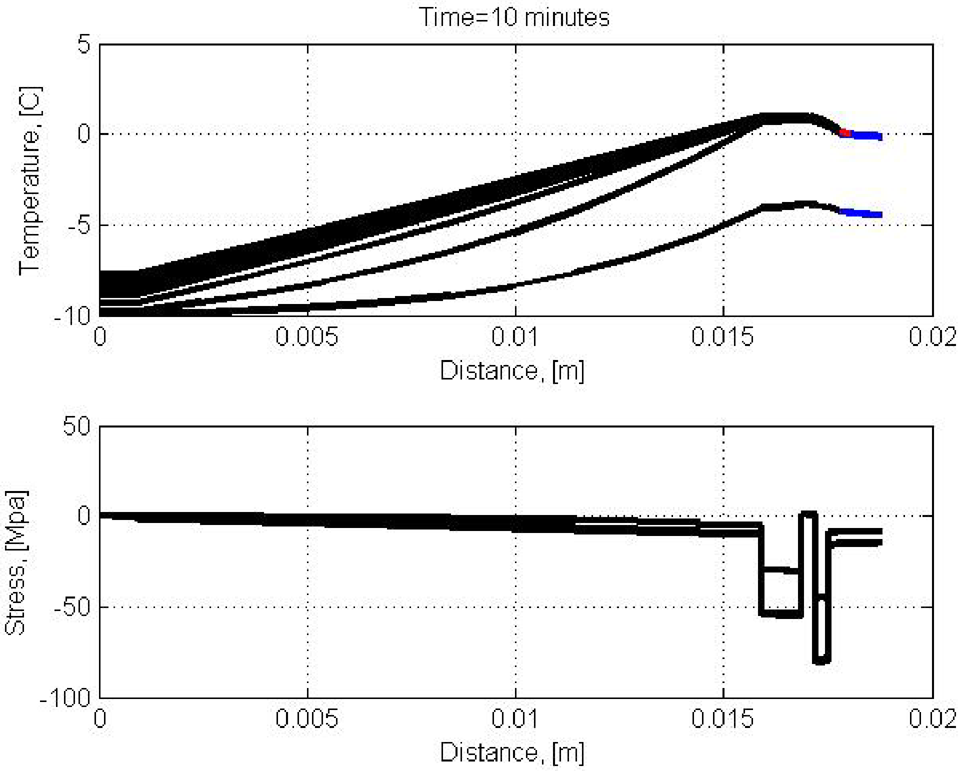


Figure 23: Simulation of the deicing process with temperature on top and stress on bottom.

The figure shows temperature at different positions in the laminate and also the ice at each minute of the deicing process. When the ice (blue) is melted the colour is changed to red to indicate water. The figure shows that the core material isolates well and most of the energy goes into the deicing process. During the first two minutes the temperature rice's quickly but when the ice starts to melt the temperature profile will be stationary in the plate. Stresses are highest in the gelcoated surface but acceptable as long as the ice is on the blades. The most severe situation is when the ice is lost and the temperature starts to rice again. In real wind turbines there will always be wind blowing on the blades which limits the temperature. The situation in the climate room is therefore not realistic but the models can easily be used together with models of the heat transfer at different wind speeds.

These models will be further developed during November and December after the final tests are performed.

Studies of the degradation due to heated laminates have been performed at Sicomp. Several details of the blade were studied in the simulations. Some of the identified effects of added heated laminate that may cause critical stresses are:

1. Uneven temperature distribution in the heated part of the laminate
2. Hot spots
3. Different thermal properties in copper and composite layers
4. Large difference in material properties between copper wire and composite
5. Large difference in material properties between the heated laminate and basic laminate.

Several student projects have been performed to evaluate different deicing techniques. The methods studied are; inflatable rubber on the leading edge to break the ice and ice-phobic coating. However, none of these methods were concluded to be suitable for wind turbines. Today we have an ongoing student project where piezoelectric plates are going to be used to create high frequency waves to separate ice from the blade. In recent papers it has been suggested and shown that the method works for steel plates but it remains to evaluate if it can be used with composites. The results from these studies will be presented in January 2015.

Two papers was planned to be published in the project. Due to bad quality of some of the results in the climate room some additional tests are needed. These tests will be performed during November and we plan to finish the papers during 2014.

Fulfilment of SWPTC's goals

Cold climate issues are a new area of SWPTC and the theme group (6) was initiated during 2012. The research from theme group 6 will contribute to increased reliability of wind power in cold climate and thereby facilitate the development of new wind farms. The research will also contribute to the possibility of new industries by developing measuring techniques and new ideas on heating systems.

Deviations from project plan

During the project we had several delays with the measurements on the real wind turbine. Flying the mini helicopter was far more difficult than expected. Today we have done a successful measurement and we expect to be able to another measurement during 2014. At LTU the main problem has been the lack of personal to work on the project. Jan-Olov got a new position at LTU when he became the chair professor of Computer Aided Design in December 2013. Jan-Olov is still working in the project but it has caused some delays in the time plan. We plan to finish the project in time at December 2014.

Publications

Two publications are planned in the project and should be finished during 2014.

External activities

The project has visited VTT to discuss their heating system.

References

[1] Manufacturing of heated test panels, Swerea Sicomp, 2014

Publications

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- H. Abedi, *Development of Vortex Filament Method for Aerodynamic Loads on Rotor Blades*, Licentiate thesis, Chalmers University of Technology, Göteborg, 2013
- J. Härsjö, *Modeling of PMSM Full Power Converter Wind Turbine with Turn-To-Turn Fault,* Licentiate Thesis, Department of Energy and Environment, Chalmers University of Technology, Gothenburg, Sweden, 2014
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- M. Khorsand Vakilzadeh, A.T. Johansson, T.J.S. Abrahamsson, *Bayesian Finite Element model calibration using manifold based Metropolis adjusted Langevin dynamics*, IX International Conference on Structural Dynamics, Porto, Portugal, June 30-July 02, 2014

- M. Khorsand Vakilzadeh, A.T. Johansson, C-J. Lindholm, J. Hedlund, T. Abrahamsson, *Development of simplified models for wind turbine blades with application to NREL 5MW offshore research wind turbine*, presented at IMAC XXXII, Orlando, Florida, USA, 3-6 February, 2014
- V. Berbyuk, B. Peterson, J. Möller, *Towards early ice detection on wind turbine blades using acoustic waves, Proc. of SPIE,* Nondestructive Characterization for Composite Materials, Aerospace Engineering, Civil Infrastructure, and Homeland Security 2014, San Diego, California, USA, March 09, 2014, 9063 pp. 90630F-1 - 90630F-11
- L. Klasén, *LIDAR Systems for Wind Energy Applications*, Proceeding of Swedish Society of Automated Image Analysis (SSBA) Symposium on Image Analysis, 2014

Submitted papers

- N. Espinoza, M. Bongiorno and O. Carlson: *Novel LVRT Testing Method for Wind Turbines Using Flexible VSC Technology*, Special Issue on Large Scale Grid Integration and Regulatory Issues of Variable Power Generation of IEEE Transactions on Sustainable Energy. Status: 3rd revision of the manuscript has been submitted for peer review in 2014-10-24
- H. Abedi, L. Davidson, S. Voutsinas, *Enhancement of free vortex filament method for aerodynamic loads on rotor blades*, Proceedings of ASME 2014 International Mechanical Engineering Congress and Exposition, November 14-20, 2014, Montreal, Canada
- H. Abedi, L. Davidson, S. Voutsinas, *Numerical Studies Of the Upstream Flow Field Around A Horizontal Axis Wind Turbine*, 33rd ASME Wind Energy Symposium, 5-9 January 2015, Florida, USA
- S. Asadi, V. Berbyuk, H. Johansson, *Simulation and analysis of dynamics of a wind turbine drive train high-speed shaft subsystem test rig, In Proc.* 27th Nordic Seminar on Computational Mechanics, NSCM-27, KTH, Stockholm, 22-24 October, 2014
- K. Frisk, C. Luo, S. Caddeo Johansson, S. Haglund, N. Petterson, I. Strandell, *Compound Materials by PM-HIP*, Accepted for publication in Powder Metallurgy
- M. Khorsand Vakilzadeh, V. Yaghoubi, A.T. Johansson, T.J.S. Abrahamsson, *Toward an autonomous modal parameter estimation framework: Mode clustering*, to appear in IMAC XXXIII, Florida, USA, 2015
- V. Yaghoubi, M. Khorsand Vakilzadeh, T.J.S. Abrahamsson, *A parallel solution method for structural dynamics response analysis*, to appear in IMAC XXXIII, Florida, USA, 2015
- C-J. Lindholm, A.T. Johansson, J. Hedlund, *Experimental analysis of stresses in sandwich structures due to the Brazier effect*, submitted to ICCM20 2015
- P. Bangalore, L. Bertling, *Self-evolving neural network based algorithm for fault prognosis in wind turbines: A case study*, to appear at Probabilistic Methods Applied to Power Systems (PMAPS), Durham, 2014
- A. Joshi, J. Blennow, Electrical Characterization of Bearing Lubricants, Conference on Electrical Insulation and Dielectric Phenomenon (CEIDP 2014), Des Moines, Iowa, U.S.A October 19th – 23rd, 2014
- J. Blennow, A. Joshi, *Current induced bearing damages in wind power applications – an attempt to understand and electrically model bearing current activity*, abstract accepted, Conference for Wind Power Drives, CWD2015, Aachen 3rd – 4th March 2015

Reports

- S. Haglund, K. Frisk, S. Caddeo Johansson, H. Kristoffersen, *Development of Compound Bearing Concept for Wind Power Applications, part 1*, Swerea KIMAB report
- V. Berbyuk, *Structural Dynamics Control, Second Edition,* Department of Applied Mechanics, Chalmers University of Technology, Göteborg, Sweden, Skrift 2014:01, 2014, 271 pages.

Master theses

- B. Jiang, *Modelling of Dynamics of Driveline of Wind Station: Implementation in LMS Image AMESim Software.* M.Sc. thesis 2010:38, ISSN 1652-8557, Chalmers University of Technology, Göteborg, Sweden, 2010
- M. Carlsson, E. Elofsson, J. Risö and D. Sandelind, *Virtuell design av en testrigg för ett vindkraftverk drivlina*, Bachelor Thesis, Göteborg, Sweden, 2012
- K. Schweigler, *Aerodynamic Analysis of the NREL 5-MW Wind Turbine using Vortex Panel Method*, Master's Thesis, Göteborg, 2012
- J. Norlin and C. Järpner, *Fluid Structure Interaction on Wind Turbine Blades*, Master thesis, Göteborg, Sweden, 2012
- F. Baldo*, Modeling of Load Interfaces for a Drive Train of a Wind Turbine*, Master's Thesis 2012:10, ISSN 1652-8557, Chalmers University of Technology, Göteborg, Sweden, 2012.
- Peter Makolo, *Wind generator Co-simulation with fault case analysis,* Master's Thesis, Göteborg, 2013
- S. G. McCann, *Design of Experiments and Analysis for Drive Train test Rig,* M.Sc. thesis 2013:30, ISSN 1652-8557, Chalmers University of Technology, Göteborg, Sweden, 2013.
- P. de Lara García, *Wind turbine database: Modelling and analysis with focus on upscaling*, Diploma work, Department of Applied Mechanics, Chalmers University of Technology, Göteborg, Sweden, ISSN 1652-8557; 2013:19, 2013
- M. Gibanica, *Experimental-Analytical Dynamic Substructuring – A State-Space Approach*, MSc Thesis, Chalmers 2013
- J. C. Squires, *Measurement System Design and Experimental Study of Drive Train Test Rig,* M.Sc. thesis 2014:36, ISSN 1652-8557, Chalmers University of Technology, Göteborg, Sweden, 2014
- T. Jungbark, *Power regulation of a vertical axis wind turbine*, MSc Thesis, 2014

Related publications

- M. Irfan, *Meta modeling of transmission error for spur, helical and planetary gears for wind turbine application,* Research report, Department of Applied Mechanics, Chalmers University of Technology, Göteborg, Sweden, ISSN 1652-8549; 2013:06, 2013
- T. J. S. Abrahamsson., and D. C. Kammer, *Finite Element Model Calibration Using Frequency Responses with Damping Equalization*, submitted to the MSSP journal.
- T. J. S. Abrahamsson and D. C. Kammer, *FEM Calibration with FRF Damping Equalization*, submitted to IMAC XXXII, Orlando, Florida, USA, 2014.
- A. T. Johansson, A. Linderholt, Y. Chen and T. Abrahamsson, *Model Calibration and Uncertainty Quantification of A600 Blades*, submitted to IMAC XXXII, Orlando, Florida, USA, 2014.
- M. Gibanica, A. T. Johansson, A. Liljerehn, P. Sjövall and T. Abrahamsson, *Experimental-analytical Dynamic Substructuring of Ampair Testbed: A State-Space Approach*, submitted to IMAC XXXII, Orlando, Florida, USA, 2014.
- *Dynamics of an offshore-based vertical axis wind turbine*, Project Report, Applied Mechanics programme, Chalmers 2013
- I. Echaniz, C. Ekberg, M. Josefsson, M. Ljungberg, J. Wass*, FE-modelling and testing of sandwich composites*, Project Report, Applied Mechanics programme, Chalmers 2014
- I. Fransen, K-J. Larsson, J-A. Lindhult, M. Gonera, A. Suryanarayana, E. Eliasson, *FE-modelling of wind turbine blade*, Project Report, Applied Mechanics programme, Chalmers 2014
- A. Brown, S. Camuz, T. Jungbark, F. Mayrhuber, A. Pakiman, M. Schreck, *Dynamics of an offshore-based vertical axis wind turbine*, Project Report, Applied Mechanics programme, Chalmers 2013
- A.T. Johansson, A. Linderholt, Y Chen, T. Abrahamsson, *Model Calibration and Uncertainty Quantification of A600 Blades,* presented at IMAC XXXII, Orlando, Florida, USA, 2014

- M. Gibanica, A.T Johansson, A. Liljerehn, P. Sjövall, T. Abrahamsson, *Experimental-analytical Dynamic Substructuring of Ampair Testbed: A State-Space Approach*, presented at IMAC XXXII, Orlando, Florida, USA, 2014
- M. Khorsand Vakilzadeh, V. Yaghoubi, T. Abrahamsson et al., *Manifold Metropolis adjusted Langevin algorithm for high-dimensional Bayesian FE*, Proceedings of the 9th International Conference on Structural Dynamics, 2014
- S. Rahrovani, M. Khorsand Vakilzadeh, T. Abrahamsson, *A Metric for Modal Truncation in Model Reduction Problems Part 1: Performance and Error Analysis*, Conference Proceedings of the Society for Experimental Mechanics Series - Topics in Modal Analysis, 2014
- S. Rahrovani, M. Khorsand Vakilzadeh, T. Abrahamsson, *A Metric for Modal Truncation in Model Reduction Problems Part 2: Extension to Systems with High-Dimensional Input Space*, Conference Proceedings of the Society for Experimental Mechanics Series - Topics in Modal Analysis, 2014
- S. Rahrovani, M. Khorsand Vakilzadeh, T. Abrahamsson, *Modal Dominancy Analysis Based on Modal Contribution to Frequency Response Function $\mathcal{H}2$-Norm*. Mechanical Systems and Signal Processing, 2014
- M. Gibanica, A.T. Johansson, S. Rahrovani, et al., *Spread in Modal Data Obtained From Wind Turbine Blade Testing*, Topics in Experimental Dynamic Substructuring, Volume 2, Proceedings of the 31st IMAC - A Conference on Structural Dynamics, 2013
- A.T. Johansson, C-J. Lindholm, M. Khorsand Vakilzadeh, et al., *Modeling and Calibration of Small-scale Wind Turbine Blade*, Topics in Experimental Dynamic Substructuring, Volume 2, Proceedings of the 31st IMAC - A Conference on Structural Dynamics, 2013
- S. Rahrovani, M. Khorsand Vakilzadeh, T. Abrahamsson, *On Grammian-based reduction methods for moderate size systems*, 19th International Congress on Sound and Vibration, 2012
- V. Yaghoubi, M. Khorsand Vakilzadeh, T. Abrahamsson, *Application of an automated modal analysis based on frequency response function estimates*, International Conference on Noise and Vibration Engineering (ISMA), 2012

External activities
International conferences
- Wake Conference June 8-9, 2011; Gotland University, Visby, Sweden
- IEA Topical Expert Meeting on Long Term R&D Needs on Wind Power, Brussels, 5th of October
- 7th PhD Seminar on Wind Energy in Europe, Rotterdam-Netherland, 26-28th of October
- EWEA 2012 Event in Copenhagen, Denmark, April 2012
- 7th IFAC Symposium on Robust Control Design in Aalborg, Denmark, June 2012
- 8th PhD Seminar on Wind Energy in Europe, September 12-14, 2012, Zurich, Switzerland
- ISMA2012 International Conference on Noise and Vibration Engineering, 17-19 September, 2012, Leuven, Belgium
- 12th PMAPS conference, Smart Grid – Smart maintenance for a sustainable power system, Istanbul, 11 June 2012
- International VDI-Conference on Maintenance of Wind Turbines, Hamburg, 8th of May 2012
- IFAC Multi-Conference on Systems Structure and Control, Grenoble, France, February 4-6, 2013.
- American Control Conference (ACC,) Washington DC, USA, June 17-19, 2013.
- EWEA 2013, Vienna, Austria, February 4-7, 2013
- EAWE 9th Ph.D. seminar, Visby, September 18-19, 2013
- 3rd International Conference E/E Systems for Wind Turbines”, Bremen, Germany, in May 2013.
- IMAC XXXII, Orlando, Florida, USA, 3-6 February, 2014
- Aerospace Engineering, Civil Infrastructure, and Homeland Security 2014, San Diego, California, USA, March 09, 2014
- International Conference SPIE2014, March 9-13, 2014

- EWEA 2014, Barcelona, Spain, 10-13 March, 2014
- 6th International Symposium on Computational Wind Engineering, Hamburg, Germany, 8-12 June, 2014
- 32nd AIAA Applied Aerodynamics Conference, Atlanta, USA, 16-20 June, 2014
- IX International Conference on Structural Dynamics, Porto, Portugal, June 30-July 02, 2014
- ECCOMAS 2014, 6. European Conference on Fluid Dynamics (ECFD VI), Barcelona, Spain, July 20-25, 2014
- FAST Workshop, Bergen, Norway, 11-12 September, 2014
- *ETMM10:* International ERCOFTAC Symposium on Turbulence Modelling and Measurements, Marbella, Spain, 17 - 19 September, 2014

National conferences
- Vindkraftsforskning i fokus 2010, Chalmers, 24-25th of November 2010
- Energiutblick, Göteborg, 15-17th of March
- Nationella Vindkraftkonferensen, Kalmar, 11-12th of May
- Vind2011, Stockholm, 14-15th of September
- Vindkraftforskning i focus 2012, Chalmers, Göteborg, 18-19 January 2012
- Energiutblick, Göteborg, 13-15 March 2012
- Nationella vindkraftkonferensen, Kalmar, 23-24 May 2012
- Wind Power Research in Focus, Göteborg, September 16-17, 2013
- Nationella Vindkraftkonferensen, Kalmar, May 22-23, 2013
- Poster presentation at ABB PhD Days, Västerås, September 23-24, 2014.

Seminars
- Havsvind, Chalmers, 21st of January, in cooperation with Power Väst
- Vindkraft för beslutsfattare, Chalmers, 4th of May, in cooperation with Power Väst
- Aerodynamics for wind turbines, 26th of May, Chalmers
- Wind energy aerodynamics - icing and de-icing of WT blades, 5th of September, Chalmers

Miscellaneous
During the project work new national and international collaborations have been established, namely with NREL, Colorado, USA on Gearbox Reliability Collaborative project, Scandinavian Wind AB, Teknikgruppen AB, University of Mons, Belgium, and with University of Aberdeen, UK.

Synergy has been obtained from a parallel project (involving the project partners Marström Composites, DIAB and the consultancy company Scandinavian Wind) that aims at developing and install new blades for Chalmers experimental wind turbine at Hönö. The manufacturing of the new blades to the Hönö 50kW machine has recently started. A measurement series will commence shortly.