Final Report

2014-2018

SWPTC

SWEDISH WIND POWER TECHNOLOGY CENTRE

Table of content

Project title	Swedish Wind Power Technology Centre
Project number	Swedish Energy Agency; P-no: 32591-2, Dnr:2014-002371
Project duration	2014-10-01 – 2018-09-30
Organisation	Chalmers University of Technology, Dept. of Energy and Environment
Report for	2014-10-01 – 2018-09-30
Project leader	Ola Carlson
Project coordinator	Sara Fogelström
Board members	
Chairman of the board	Matthias Rapp
Academic partners	Luleå University of Technology, Swerea, Chalmers University of Technology, RISE
Industrial partners	Göteborg Energi, NCC Sverige, Röbergsfjället Vind
Theme group leaders	Ola Carlson, Division of Electric Power Engineering, Dept. of Electrical Engineering, Chalmers
	Lars Davidson, Division of Fluid Dynamics, Dept. of Mechanics and Maritime Sciences, Chalmers
	Viktor Berbyuk, Division of Dynamics, Dept. of Mechanics and Maritime Sciences, Chalmers
	Rasmus Rempling, Division of Structural Engineering, Dept. of Architecture and Civil Engineering, Chalmers
	Michael Patriksson, Division of Mathematics, Dept. of Mathematical Sciences, Chalmers
	Johan Casselgren, Fluid and Experimental Mechanics, Department of Engineering Sciences and Mathematics, Luleå Technical University
Project partners	ABB, Awind, Blade Solutions, Greenbyte, Hexicon, Meventus, MHI Vestas Offshore Wind (MVOW), Rabbalshede Kraft, SeaTwirl, Skellefteå Kraft, SKF, Stena Renewable, Svenska kraftnät, Vattenfall

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 construction and maintenance of wind turbines and ultimately to reduce the cost of electric power to consumers. During stage 1, competence within several relevant fields of technology were created. Now in stage 2, this competence has been developed further and the knowledge within wind power technology has increased.

The Centre concentrated on wind turbines with a capacity of more than 2 MW, suitable for positioning in open countryside, in forests, in cold climate or offshore.

The academic partners within the Centre have been Chalmers University of Technology, Luleå University of Technology, RISE and Swerea. Göteborg Energi, NCC Construction Sverige and Röbergsfjället Vind, Winfoor, Marström Composite and Vindmark Technologies have been industry partners the whole or parts of stage 2. Furthermore, 14 companies have been project partners in specific projects: ABB, Awind, Blade Solutions, Greenbyte, Hexicon, Meventus, MVOW, Rabbalshede Kraft, SeaTwirl, Skellefteå Kraft, SKF, Stena Renewable, Svenska kraftnät and Vattenfall. In total, 20 industry partners have been involved in projects within SWPTC.

SWPTC has organised its work in six theme groups.

- Power and Control Systems
- Turbine and Wind Load
- Mechanical Systems and Structures
- Offshore
- Maintenance and Reliability
- Cold Climate

The research has been carried out in project form in close cooperation with industry, mainly for detailed research efforts for deep knowledge as well as one broader project that covers several of the theme groups. The large project focuses on a complete design which takes the interaction between several components into account to estimate the remaining lifetime of a wind turbine due to operation conditions.

At Chalmers there are five divisions active in SWPTC; Electric Power Engineering (including High Voltage Engineering), Dynamics, Fluid Dynamics, Structural Engineering and Mathematics. The division of Fluid and Experimental Mechanics at Luleå Technical University, Swerea Sicomp and RISE also work within the Centre. The Centre is unique in the way that many divisions, from several areas of research, cooperate in one Centre.

Results

During stage 2, the Centre has had 22 on-going projects. Eight projects are PhD project extended from stage 1, three are new PhD projects and two are short extensions of senior researcher projects from stage 1. The remaining nine projects are new senior research projects, ranging from small prestudies and support projects to big projects encompassing all expertise within the Centre.

The Centre projects have employed 11 PhD-students and five senior researchers. Around ten permanent employees at Chalmers have been engaged as supervisors or project leaders on a part time basis, mainly at professor or associate professor levels. Around 25 people from the industry partners also work with SWPTC projects. During this period the Centre has generated about 48 full-time equivalents of work.

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

During the reporting period, the wind power content of several Master of Science courses at Chalmers were developed and held as specific assignments in more general courses, with electrical, mechanical as well as mathematical content.

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 measurement in a wind tunnel, made a measurement campaign with Lidar, built up laboratory test objects of the electrical and mechanical drivetrain of a wind turbine, as well as made tests in Swerea's labs.

The detailed results are described in the respective project report.
During stage 2 the Centre has:

- Developed new methods for maintaining turbines
- Developed enhanced calculations methods within aerodynamics and structural dynamic
- Developed test method for grid codes
- Developed knowledge about manufacturing of bearings and bearing currents
- Developed fault detection method in generator
- Developed models of the drivetrain and the forces that rises
- Shown that wind turbines in forest experience higher loads

- Identified possible sources of unstable resonances in the voltage of a wind-farm HVDC system such as converter control parameters as well as the nature of passive components and suggested possible preventive methods
- Developed a method for calculating the lifetime of a specific wind turbine from geographic and operation data
- Developed a model for prediction of gearbox motion under operation
- Studied the aerodynamic and structural properties of the novel Triblade concept
- Developed an enhanced and generic three-dimensional strut and tie model for the design of reinforced concrete foundations and validated with experimental results from tests on four-pile caps
- Developed knowledge and deeper understanding of the dynamics and fatigue loads of a vertical axis wind turbine and its interaction with the support structure
- Developed a method for detection of cable breakage and repair methods in the blade for cables to the heating system for de-icing

Finances

During the four years, the Centre has received 48 024 375 SEK in gross revenue, whereof 67 % comes from the Swedish Energy Agency, 17 % comes from member companies and project partners and 17 % from the Academic partners. The total cash budget for SWPTC was 48 million SEK. The costs during stage 2 have been 47 375 067 SEK. Therefore, stage 2 ends with a plus result at 289 308 SEK

83 % of the received funding has been used for approved projects. The remaining sum has financed the Centre management as well as the research management carried out by the theme group leaders.

During stage 2, all in-kind work has been carried out. The industrial companies have carried out 110 % of their share, and the academic partners have carried out 112 % of their share.

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

Other internal activities

Every year, 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 2 SWPTC has had 16 Board meetings, two Partner meetings and two per capsulam descions.

Deviations from project plan

During this period there has been no delays and the Centre is in phase with the time plan.

Publications during this period

The Centre has published 15 journal papers and 23 conference papers during stage 2. Seven more papers have been submitted for conferences and journals during this period. Four reports have also been written during stage 1. Seven Doctoral theses and one Licentiate thesis have been presented during this period.

Ten Master theses have been carried out in cooperation with SWPTC-projects during stage 2.

External activities

SWPTC organised the conference Vindkraftsforskning i fokus twice during this period: in October 2015 and in April 2017 together with the other wind related research programmes in Sweden.

During this period SWPTC has participated at four board meetings within European Academy of Wind Energy (EAWE) in Lyngby, Denmark in June 2017, in Cranfield, Great Britain in September 2017, in Milano, Italy in June 2018 and in Brussels, Belgium in September 2018.

SWPTC has also participated in EERA's annual event in September 2018. The Centre also represented Sweden at på IEA Wind Task 11- Topical expert meeting on a Grand Vision for Wind Energy, meeting #89.

Projects

The Centre have had 22 on-going projects. Eight projects are PhD project extended from stage 1, three are new PhD projects and two are short extensions of senior researcher projects from stage 1. The remaining nine projects are new senior research projects

Project title	Wind turbines under harsh operation conditions
Project number	TG0-21
Organisation	Chalmers University of Technology, Electric Power Engineering, Fluid Dynamics, Dynamics, Structural Engineering
Project leader	Ola Carlson
Other participants	See table below
Report for	2014-10-01 – 2018-09-30
Participating companies	AWind, NCC, Rabbalshede Kraft, Röbergsfjället Vind, Skellefteå Kraft, SKF,

Academic partners

Division	**Person**	**Title**
Fluid Dynamics	Lars Davidson	Professor
Fluid Dynamics	Hamid Abedi	Doctor
Dynamics	Viktor Berbyuk	Professor
Dynamics	Håkan Johansson	Associate Professor
Dynamics	Thomas Abrahamsson	Professor
Dynamics	Majid Khorsand Vakilzadeh	Doctor
SWPTC	Sara Fogelström	Coordinator
Structural Engineering	Structural Engineering	Alexandre Mathern
Electric Power Engineering	Ola Carlson	Associate Professor
Automatic control, Automation and Mechatronics	Sebastian Gross	Associate Professor

Industry partners

Röbergsfjällets vind AB	Tord Östlund
Rabbalshede kraft AB	Björn Johansson
Awind AB	Anders Wickström
SKF	Olle Bankeström
Skellefteå kraft	Henrik Renberg
NCC	Jonas Magnusson

Project description

This project focused on the harsh operational conditions that sometimes lead to gearbox and bearing failures before their expected lifespan has been reached. Individual wind turbines that are subjected to extreme wind conditions and otherwise severe operational conditions has been identified in close cooperation with wind turbine operators. Methods for determining the operational severity from data acquired during operation have been developed to obtain relevant operational severity indices. Raw measured data has been processed and compared to the assumed data that was used in the wind turbine design process. Feedback from maintenance reports have been used to strengthen the relevance of these indices. A multiphysics model have been incorporated for simulation of the wind turbine dynamical behaviour under the conditions given by measured wind and grid dynamics. The project has used the synergy of the competences developed within all different competences of SWPTC's.

The assessment has been made using 17 wind turbines of same design but with different operational conditions. Comparisons have been made between data from these turbines, and comparison has also been made using simulated data for complex and flat terrain. The results showed that the complex terrain increased the fatigue on the gearbox shaft and the fluctuation of wind direction in the complex terrain were much higher than for the flat terrain, resulting in more destructive fatigue loads. Simulation also shows that de-rating of the turbine had a significant impact on the loads in the drive train but no significant impact on the fatigue loads on the nacelle.

Results

The results are described per work package in the project, see below.

WP1: Project organisation

A detailed work plan has been established, monthly planning meetings have been carried out, workshop for gearbox examination has been organised and work meetings regarding simulation of the wind turbine have been carried out regularly.

WP2: Case studies

The wind turbines operators and owners have informed about their wind turbine fleets and clarified which wind turbines that are available for the study, altogether 75 wind turbines from four manufactures.

There were different systems running for capturing operational data during operation. The "Breeze data" was available for the whole fleet of wind turbines. However, the data resolution was poor. Normally Breeze stores only one measurement data point at each 20 second, i.e. 0.05 Hz. Then it was difficult to observe any details related to loads based on turbulence or other environment or technical conditions. For that reason, the project strived and managed to get higher resolution measurement data for specific turbines in the available fleets. The data came from Vestas which provided some general data with 1 Hz resolution. For this reason, in combination with the failure rates and model parameters availability, the project concluded that Vestas V-90 turbines was the type of turbine that should be studied.

WP3: Fluid dynamics

The complex topography of Röbergsfjället wind farm was extracted from LASer data (LAS file), obtained from SLU (www.slu.se), using a commercial software called Global Mapper; and it was imported into STAR-CCM+ to generate the computational grid for the numerical simulations. The on-site meteorology mast data, provided by project partners, were used to determine the dominant mean wind speed/direction and turbulence intensity. These data were also used to validate the numerical modelling. The numerical simulations were done over the complex and flat terrains. For this purpose, a high-fidelity approach, Large-Eddy Simulation (LES) was employed over a computational domain of size L=10 km x W=10 km x H=2 km, to simulate the atmospheric turbulence and time-varying wind profile for a period of 10 minutes. The surrounding area of Röbergsfjället wind farm is covered partly by farmlands and partly by dense forest. However, in the numerical simulation, it was assumed that the complex and flat terrains are covered by a horizontally homogeneous forest with a height of 20 m.

The results showed that the time-averaged stream wise velocity over the complex terrain was higher than over the flat terrain. This could be explained as the well-known phenomenon - the so-called speed-up - which occurs over hills/mountains. Contrary to the flat terrain, the mean flow passing over the complex terrain was deflected laterally and vertically while the lateral deviation was greater than the vertical one. Therefore, all turbines located in the complex terrains were continuously exposed to more violent yawed and inclined flows compared to the flat terrains. As a consequence, wind farms located in complex terrains suffered from large fluctuating forces acting on rotor blades resulting in higher fatigue loads, higher maintenance costs and shorter lifetime.

WP4: Nacelle and drive train

The very dominating load, affecting the internal parts of the gearbox, was the drive torque on the shaft. This torque was related to the power output of the turbine. By reducing the power at the same rotor speed, the loads acting inside the gearbox was reduced with the same portion. This high number of load/stress cycles should be below the theoretical "Cut-off limit" in design standards, where 1E+8 load cycles are defined as a limit for infinite life. But the absolute difference for infinite life was small. Wear and tear, loads close to the cut off limit, were likely to cause a small slope also above 1E+8 load cycles. This high cycle slope might be crucial for the life of the gearbox component.

In combination with nacelle bending moment, which might cause displacements in the gearbox housing, leading to non-uniform internal loadings, the harsh conditions created a load situation which was above the design requirements of the gearbox. Relatively small constraints in maximum power output might be the difference between limited and infinite life.

WP5: Mechanical loads and aging of towers and foundations

A common approach for the design of foundation is that the turbine and foundation are usually analysed separately and the loads used to design the foundation are calculated assuming a rigid foundation. This way of designing has its limitations and will influence the design loads crucially for stability/durability, especially for larger wind turbines and poorer soil conditions. The effect of soil-structure interaction (SSI) on the design of gravity foundations for wind turbines was studied by implementing SSI in the open source aero-servo-elastic simulation tool FAST. A parametric study was conducted to investigate the influence of SSI for different soil conditions. The study showed the potential impact on the fatigue loads and the natural frequencies of the system. The stability of a foundation is conventionally checked with empirically developed formulas. A comparison was conducted by computing a three-dimensional yield surface for a shallow foundation under combined loading (horizontal and vertical forces and moments). It was shown that this method leads to less conservative results.

There are numerous reports from Sweden and abroad of cracked concrete foundations of wind turbines but there is lack of details on their causes and consequences. Observations and recommendations of measures for preventing low quality foundations have been summarized in a paper.

WP6: Electric drives and grid disturbance
Transient models of grid, converter and generator during grid disturbance has been developed in previous projects and have been used in this project. Typical voltage dips in the grid were the inputs for the simulations. The results showed that there was a significant torque peak from the generator when there was a large voltage dip in the grid. The peak could be as high as the rated torque doubled and the duration was around 50 ms. The peak occurred when the voltage came back after the dip. But the torque peak was very short, and the softness in the generator rotor, the shaft and the mechanical coupling to the gearbox absorbed the force and there was only a minimal extra torque on the gearbox shaft.

WP7: Control to reduce the load
The actual V90 control system was unknown to the project participants. But from analyses of the measurement data, the control system could be predicted. It was noted that the V90 turbine operates at constant rated rotor speed above a certain power which is below rated power. As a starting point, an open source controller (NREL 5 MW) were evaluated. By parameter substitution and tuning, a very good agreement were obtained when comparing the measured 1 Hz data with the simulation output when using the adapted generic controller.

It has also been shown that the constant rotor speed at various power output can be achieved by using a PI-controller for the torque setting in medium wind speeds. Source code and parameter settings were part of the project results. However, what were a bit tricky was the transition criteria between different regions. Therefore, the robust NREL controller has been used for the load calculations. The differences in loads were insignificant.

The major control action to reduce the loads is the power output. From comparisons of different power settings the following conclusions were reached:
The fatigue loads were far from equal for wind class II conditions rated 1.8 MW compared to wind class III conditions rated 2.0 MW.
De-rating of the turbine had significant impact on the loads in the drive train but no significant impact on the fatigue loads on the nacelle.

WP8: Simulation of the wind turbine
This work package summarised the steps needed to generate a new wind turbine blade model for aero elastic simulation purposes. This was also to provide knowledge and hints for other research activities, where new generic turbines were requested and required. Besides the new V90 blades, a whole generic V90 turbine has been created for the simulations in the project. This input parameter design work has been used to simulate V90 using both FAST and VIDYN aero elastic simulation codes. A system simulation model in FAST or VIDYN could reasonably well predict the hub forces and nacelle motions of a Vestas V90 turbine under different kind of wind load in operation.

WP9: Multidisciplinary questions
Based on the various subsystems dealt with in WP 2-8, issues arising from the various subsystems have be studied, such as how the turbulent wind creates forces on the shaft and gearbox and can grid disturbance create a damage on the generator and also damage the gearbox? Can turbulent and gusty winds create additional stress on the foundation? Just to name a few issues. Some answers have been created such as that fast generator torque fluctuations was not transferred to the gearbox shaft. But it is clearly shown that complex terrain create more turbulence and there by more loads.

WP10: Measurements and measurement system

In collaboration with the wind turbine owner the project managed to receive measurements from the sensors of wind speed, wind direction, yaw position, pitch angle, rotor speed and generator power with the sampling rate of 1 second. The measurements with the sampling frequency of 1 Hz were collected for 16 wind turbines from June 2017-October 2018. Similar measurements from a V90 in flat terrain from a previous project has also been used for comparison. A number of measurements were collected and correlated with data of gearbox repair.

An additional measurement campaign, contributed by QUALISYS, that was based on optical measurement of gearbox motion, was evaluated for one turbine. This study revealed the possibility to evaluate turbine performance based on motion tracking of gearbox.

Fulfilment of SWPTC's goals

The main aim of SWPTC is to develop knowledge of the full wind turbine system through deep understanding of the system components and their interaction with the support of Multiphysics simulation. This project was in line with that aim since it targets the complete wind turbine structure with analysis based on a synergy of theory, modelling and collected operational data from sensors.

Wind turbines always operate within the Atmospheric Boundary Layer (ABL) and are therefore subjected to atmospheric turbulence. Therefore, prediction of flow field is extremely important for design, development and optimization purposes. In the project, advanced computational methods for more accurate prediction of atmospheric boundary layer over complex terrains were developed. This lead to:

- Assessing the economic feasibility of a wind turbine farm project
- Increased lifetime of wind turbines
- Reduced operating and maintenance costs

Deviations from project plan

The main goals of the project have been fulfilled.

Publications

No publications so far, a large technical report have been written and a scientific journal paper is planned.

External activities

Presentations on wind power conferences are planned during the coming year.

Project title	Chalmers wind turbine set in operation for research
Project number	TG0-22
Organisation	Chalmers University of Technology, Electric Power Engineering
Project leader	Ola Carlson
Other participants	
Report for	2018-06-01 – 2018-09-30
Participating companies	Modvion

Project description

Today Chalmers wind turbine is under reconstruction, it will soon be in operation with three new carbon fibre blades, new electrical pitch control system, including a new hub. The control computer is also upgraded and a new site for test station is under development. This project has contributed to the finalization of the construction of the wind turbine and the new test station. The main work of the relocation and construction is carried out within a project supported by Västra Götalandsregionen. This project has mainly contribute to the design, drawings and construction of wiring and connection of sensors, amplifiers, pitch system, tower cables and control system.

Results

WP1: Project organisation has been carried out and work meetings regarding simulation of the wind turbine and progress of the construction work have been carried out regularly.

WP2: Control studies, the WP include three practical steps, simulation by Matlab and FAST, programming in Labview and finally test the operation in real time on the wind turbine. The theoretical part of this WP has partly been a collaboration with the division of Automatic control and carried out by a guest researcher. The test of operation in real time have not been carried out as planned.

WP3: Safe design of the rebuilt wind turbine is an important issue, investigation of the yaw bearing and the joint between the tower and the bearing and the joint between the bearing and the nacelle has been carried out. The design of the investigated parts is still within the safe margin, even if the turbine diameter has increased. The fatigue loads are on the limits, and the wind turbine could not be used in continuous operation for several years. This is not a problem due the use of the turbine is only for experimental short time operation. The joint between the tower and the bearing is reinforced with new bolts and new screw threads.

WP4: Cabling of blade sensors and pitch motors, the wind turbine has three blades and each blade is equipped with 8 sensors for measuring the movements in the carbon fibres, every sensor has 6 wires, and every wire has an overvoltage-protection to avoid lighting damages and are connected to a rotating connection box inside the nacelle. The work with design of the lighting protection and carrying out of all the wiring for connections to the power supply and the measuring computer has been done.

WP5: Design and wiring of the rotation connection box in the nacelle
The rotating connection box on the main shaft in the nacelle contains the signal amplifiers for the blade sensors and makes it possible to connect different sensors to the amplifier. The amplifier for torque measurements on the main shaft as well as a part of the measurement and control computer system is also located in the box. The output signals from the rotating box is connected to the main computer via the slip-rings in the nacelle and the power supply to the rotation parts is also done by the sliprings. The work in this WP has been designing the rotating box and carry out the wiring.

WP6: Design and cabling the connection box in the nacelle
The accelerometers and the yaw system signals in the nacelle is connected to the tower cables via a connection box. All the signals from the sliprings is also connected in the box on the way to the tower. The work has been to design the connection box and carry out the wiring.

WP7: Design and cabling of the tower cables
The cables in the tower is a mixture of signal and power cables that are closely mounted. It is a demanding design to select the cables to avoid disturbance in the signals from the power currents. The main work in this WP is to select the tower cables and make a nice package that can be installed in the tower. The cables have been delivered to the workshop.

WP8: Assessment of sensor technology for structural health monitoring of concrete foundation and load transfer from turbine to ground

The use of embedded sensors in concrete structures to monitor their real-time condition by measuring parameters such as temperature, moisture and strains has been, until today, a great challenge. However, due to the combination of existing technologies in various fields, promoted by the close collaboration between academia, sensor producers, information technology companies and the construction industry, this has now become feasible. Therefore, this is a unique opportunity to test the use of embedded sensor in a real life structure subjected to the severe weather conditions of the west coast of Sweden. The main work in this WP is to purchase the sensors and install them in the concrete foundation. The work has not been done due to the delay of the building permit for the new test station.

WP9: Construction of new test site and foundation

Due to the development plans on Hönö island in Öckerö municipality there is a need to move Chalmers test station for wind power from Hönö to Björkö. The foundation is already designed in another project and adapted for testing a 30 m wooden tower. A new road and a new foundation was planned to be done in this WP. Unfortunately, the building permit for the new test station has been delayed and thereby no activity in this WP.

Fulfilment of SWPTC's goals

The main goal of the SWPTC is to develop knowledge of the full wind turbine system through deep understanding of the system components and their interaction. This project is in line with that aim since it targets the complete wind turbine structure with analysis based on a synergy of theory, modelling and collected operational data from sensors.

Deviations from project plan

The main goals of the project has been fulfilled. But the work related to the foundation and road construction has not been carried out due to the delay of the building permit for the wind turbine.

Publications

No publications so far, an internal working technical report is written. The design and construction of the wind turbine has been presented for possible international cooperation partners, and the wind turbine has been a part of international project proposals.

External activities

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	2014-10-01 – 2016-12-31
Participating companies	Göteborg Energi

Project description

The goal of the project was to further develop the models of the generator during internal turn-to-turn short-circuit to attain knowledge which can be used in the development of fault detection methods. The generator type investigated in this project was the permanent magnet synchronous machine (PMSM), which is used in the Big Glenn wind turbine in Gothenburg. According to the performed literature study, the turn-to-turn fault is the most common electrical fault for electrical machines but any effective fault detection method for this type of fault does not exist. Hence, the modelling of PMSMS with turn-to-turn fault with the aim of using the developed models for generating knowledge that could be used for fault detection was selected as the topic for this project. The generator was modelled both analytically and using finite element software, where the finite element model was used for both the verification of the analytical model, and to evaluate the faults impact on the electromagnetic forces of the generator.
The project description was specified in the following subtasks:

1. Further improve the models derived in stage 1 in order to increase model accuracy and investigate additional aspects of the model which were not considered in the first part, such as magnetic saturation. In addition, the models should expand the model so that it is able to model machines with parallel winding, which is common for larger machines such as the ones used in wind turbines.
2. Investigate the machine controller reaction to operating a faulted machine. The introduction of a controller can introduce new, more effective quantities to monitor for fault detection other than the machine current as presented in stage 1.
3. Use the FEM models to investigate the faults impact on the electromagnetic forces of the machine.
4. Verify the simulation results in an experimental setup consisting of a purposely rewound machine, where the rewinding allows the possibility to short-circuit some of the machine turns in a controlled manner. The experimental testing includes both the fault impact on the machine currents and the faults impact on the electromagnetic forces of the machine.

Results

The derived analytical model presented comparable simulation results as the FEM models, where the benefit of the analytical model was that it could be simulated in the range of seconds to minutes where an equivalent simulation of the FEM models would take hours or days. The analytical model has been verified for various operational conditions; generator operation with a pure resistive load for various loads and speeds and during ideal converter operation. Figure 1 and Figure 2 presents the simulation results where the faulted FEM and analytical model are compared during dynamic simulation where a machine current controller was used to achieve the desired machine torque.

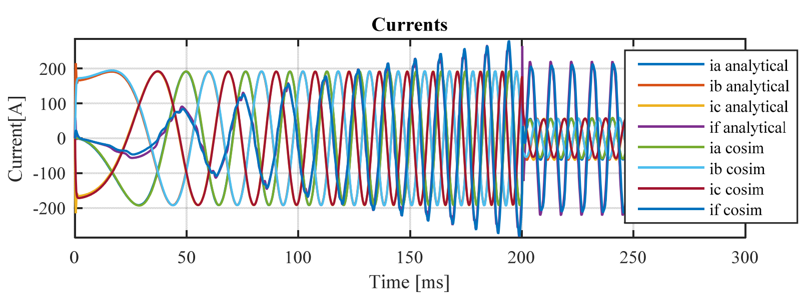


Figure 1 Currents and torque from analytical model and the co-simulation which includes the FEM model during ideal converter operation. The torque reference is stepwise reduced from 100 Nm to 30 at 200 ms.

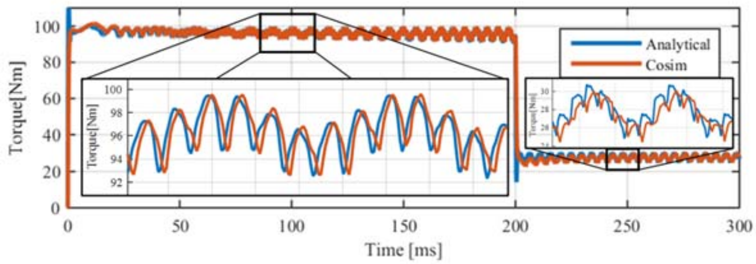


Figure 2 Currents and torque from analytical model and the co-simulation which includes the FEM model during ideal converter operation. The torque reference is stepwise reduced from 100 Nm to 30 at 200 ms.

The analytical model was extended so that it was able to model machines with parallel windings, where it was generically extended so that any number of parallel windings could be included in the model. The circulating currents which occurred due to the turn-to-turn fault (because of the reduced induced voltage in that branch compared to the non-faulted branches) for machine was investigated and it was concluded that for less sever faults the circulating current was less than rated current and should therefore not pose any major issues for the machine. However, even though the amplitude of the circulating current may be very large, the fault current in the short-circuited loop typically was several times greater than the rated current the machine should therefore be stopped in order to limit the damage.

A turn-to-turn fault will (because of its inherent nature of the fault current to oppose any change in flux) not introduce any additional saturation in the machine, if anything it will reduce the saturation level. As a result, if a linear model of a non-faulted machine presents acceptable results with the modelled machine during normal operation, then a linear model of the faulted machine will present similar agreement.

With the implemented control structure, it was proven to be more effective to monitor the machine power rather than the machine currents (as suggested in the first part), as the fault consumes some power the controller compensates, which results in less power than what to be expected during generator mode. The fault introduces torque oscillations, which results in power oscillations since the controller tries to keep the speed of machine constant. Figure 3 presents the machine torque for various degrees of short-circuited faults. The machine model used in this simulation consists of 20 turns in one phase, i.e. one turns fault equals 5% of the phase being short-circuited. There were other electrical quantities that could be used such as the amplitude of the current harmonics or the phase angle of the current, but these quantities were not very effective to use as early detection when only a single or very few turns were short-circuited.

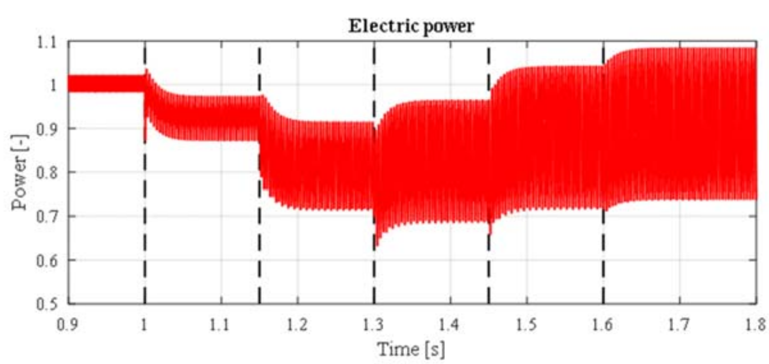


Figure 3 The output power of the converter driven model during generator mode.

The faults impact on the electromagnetic forces was investigated to see if the fault could more effectively be detected using the mechanical vibrations of the machine frame instead of any of the electrical quantities. Because the fault opposes the change in the airgap flux, the symmetry of the airgap flux is lost resulting in an unbalances attraction force between the rotor and the stator. Figure 4 presents the radial normal force in the airgap (attraction force between rotor and stator) at a single time instant, and as can be seen, the normal force for the non-faulted machine presented similar values at 10° and 190°

(mechanical). As these forces were 180° separated, they were in opposing directions which resulted in a force close to zero. In the case of the faulted machine the normal force was reduced at 10°, hence the resulting force for the faulted machine was no longer zero. This difference resulted in increased vibrations with a frequency at two times the fundamental frequency; it was two times frequency as the orientation of the magnets does not matter as the fault opposes changes in flux regardless.

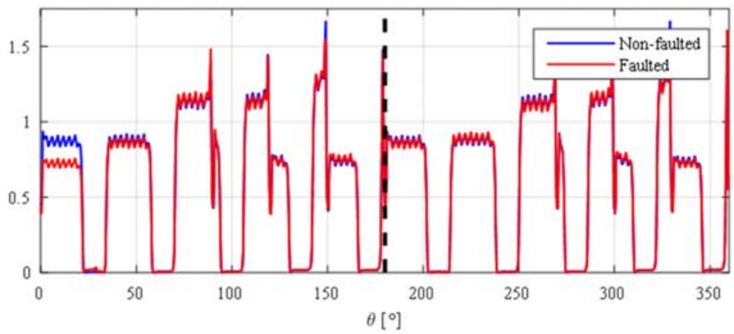


Figure 4 Normalized normal component of the air-gap flux density for one time instance during generator operation for faulted and non-faulted machine model.

Using a test setup in the lab, the simulation results was verified. The setup used a rewound machine which had access to inner parts of the winding so that up to 4 turns (about 0.5% of the total phase winding) could be short-circuited. As was done for some simulations, the test setup was operating as a generator with a resistive load. Because of the relatively small portion of the machine being short-circuited, the impact on the machine current was not measurable, showing that monitoring the current harmonics is not the most effective detection method for small fault. However, the fault caused a measurable difference in the machine vibrations, as the amplitude of vibration at two times the fundamental (electrical) frequency increased, see Figure 5. The non-integer was caused by the slightly oval shape of the machine used in the lab setup.

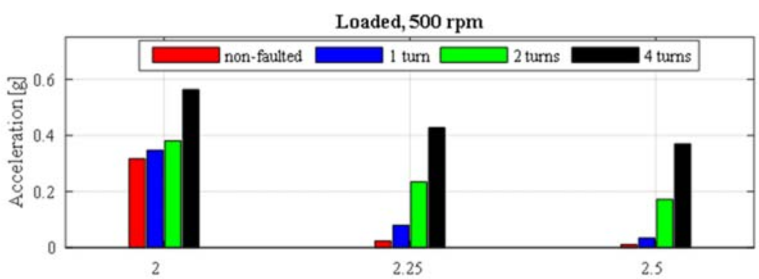


Figure 5 Fourier analysis of the measured stator vibrations while the machine was rotating with 500 rpm during generator operation with a pure resistive load.

To summarize, the turn-to-turn fault affects the electrical quantities of the machine but the most effective way to detect the fault was to monitor the machine vibrations as it was able to detect even fault consisting of only a single to a few turns.

Fulfilment of SWPTC's goals

This project helped fulfilling SWPTC's goals such as development of the electric drive train, optimizing the entire turbine and it was contributing the wind power technology knowledge in the engineering education.

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

Deviations from project plan

No deviations from project plan

Publications

Doctoral thesis

J. Härsjö, *Modeling and analysis of PMSM with turn-to-turn fault*, Ph.D. thesis, Chalmers University of Technology, 2016

Conference papers

J. Härsjö, M. Bongiorno, *Modeling and harmonic analysis of a permanent magnet synchronous machine with turn-to-turn fault*, 2015 17th European Conference on Power Electronics and Applications (EPE'15 ECCE-Europe), 8-10 Sept. 2015, Geneva, Switzerland

Submitted papers

J. Härsjö, M. Bongiorno "Analytical and FEM Modeling of a PMSM with a turn-to-turn fault" Submitted to IET-Electric Power Applications

J. Härsjö, M. Bongiorno "Impact of turn-to-turn faults on the electromagnetic forces in a Permanent Magnet Synchronous Machine (PMSM)" Submitted to IET-Electric Power Applications

External activities

No external activities.

Project title	Frequency characterization and model verification of wind turbines systems by VSC-based testing equipment
Project number	TG1-4
Organisation	Chalmers University of Technology, Electric Power Engineering
Project leader	Ola Carlson
Other participants	Nicolas Espinoza (PhD student)
Report for	2014-10-01 – 2016-09-30
Participating companies	Göteborg Energi

Project description

The goal of the project was to investigate the application of VSC-based testing equipment for model validation of wind turbines.

The advantages and limitations of the use of VSC-based testing equipment for model validation and testing of wind turbine have been investigated in Stage 2. That included frequency characterization of wind turbine to detect possible control interaction between wind turbine and the interconnecting system i.e. HVDC or AC collector grid and testing of the generating unit for different scenarios for both normal and faulty condition of the grid. The project included a comprehensive comparison between the developed simulation model and a small-scale wind turbine laboratory model in terms of electromagnetic transient behaviour and frequency characteristics to assess verification methodology of wind turbines system by means of VSC-based testing equipment.

In particular, the research project in stage 2 have covered the following aspects: Frequency characterization of both DFIG and full-size converter wind turbines by VSC-based testing equipment; Development of a small scale full-size wind turbine drive train for frequency characterization by LV prototype of VSC-based testing equipment and comparison of frequency characteristic between simulation and laboratory model. In addition, the development of testing methodology of wind turbines during normal and faulty condition of the connecting grid includes: Testing of control strategy during LVRT event and grid code compliance; Testing of frequency control during grid frequency fluctuations; Testing of power oscillation damping capabilities of wind turbine by emulating an oscillatory grid in the test equipment.

The investigation conducted during stage 1 was mainly focusing on grid code testing of wind turbines by using a VSC-based testing equipment. The control of the 2-level VSC both for the wind turbine and for the testing equipment was studied in detail. That includes the classical control algorithms (such as current controller, phase-locked loop, ac and dc voltage controllers) as well as the implementation of control strategies for the wind turbine during fault conditions and hardware protection. In addition, the ability of the modelled generating unit to provide additional features such as voltage control and reactive power support (both during normal and faulty condition of the grid) has been also verified thorough laboratory experiment. The knowledge acquired during stage 1 have been the basis for the continuation of the project.

Finally, part of the work have been laboratory experiment including the use of LV prototypes for model validation and full power test at the 4 MW wind turbine in Göteborg. The activities of the project during stage II have been divided in work packages, in correlation with the description given above:

1. **Reporting** of by seminars, scientific papers and Licentiate thesis and PhD thesis. Collaboration and communication with other projects within SWPTC is also included in this task.
2. **Laboratory work** as continuation of stage 1. That includes laboratory experiment of VSC representation of two area mode power oscillation at the PCC; and frequency spectra characterization of the test object carried out by VSC. Full power test at the 4 MW wind turbine in Göteborg is also included in this task.
3. **Study of wind power systems:** Study of the impact of non-linear conversion systems in the drive-train electromechanical dynamics. Study of possible interactions between wind turbines and interconnecting systems e.g.: control interaction with HVDC systems, sub-synchronous resonances in AC collector systems.

4. **Simulation** of the wind turbine system model including its control system and modulator and grid interface. Research activities conducted in WP5 will be also supported by modelling and simulation. In particular, frequency characterization of both DFIG and full-size converter wind turbines by VSC-based testing equipment.
5. **Validation of wind turbine model:** Development of a small scale full-size wind turbine drive train for frequency characterization by LV prototype of VSC-based testing equipment; Comparison of frequency characteristic between simulation and laboratory results; The development of testing methodology of wind turbines during normal and faulty condition of the connecting grid includes: Testing of control strategy during LVRT event and grid code compliance; Testing of frequency control during grid frequency fluctuations; Testing of power oscillation damping capabilities of wind turbine by emulating an oscillatory grid in the test equipment.

Results

The setup shown in Figure 6 has been modelled in the time-domain simulation software PSCAD.

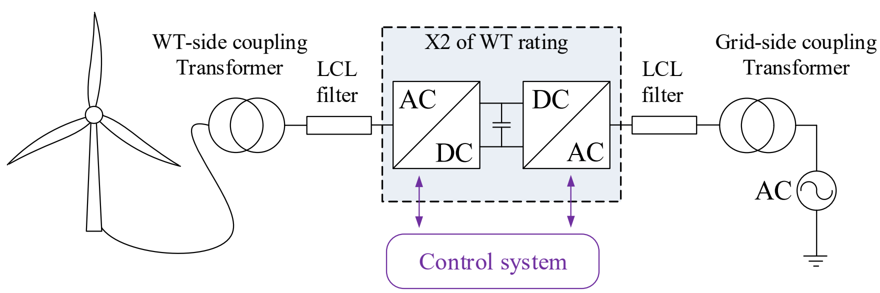


Figure 6 Wind turbine connected to a Back-to-back VSC –based testing equipment.

A discrete control algorithm has been developed in order to control both the testing equipment and the wind turbine model. A stability analysis has been carried out to identify sensitive settings of these two objects. Laboratory experiment has been carried out to validate the results included in the Licentiate thesis. New results included in a new scientific paper and also in the PhD thesis includes the calculation of the wind turbine admittance. The admittance was calculated as an average of the phase admittance. The system was exited with a reduced voltage at the frequency of interest, while the current at that frequency was retrieved by FFT analysis. The test has been carried out in simulation, laboratory and field test environment.

The main results were the calculation of the wind turbine admittance. The admittance was calculated as an average of the phase admittance. The system was exited with a reduced voltage at the frequency of interest, while the current at that frequency was retrieved by FFT analysis.

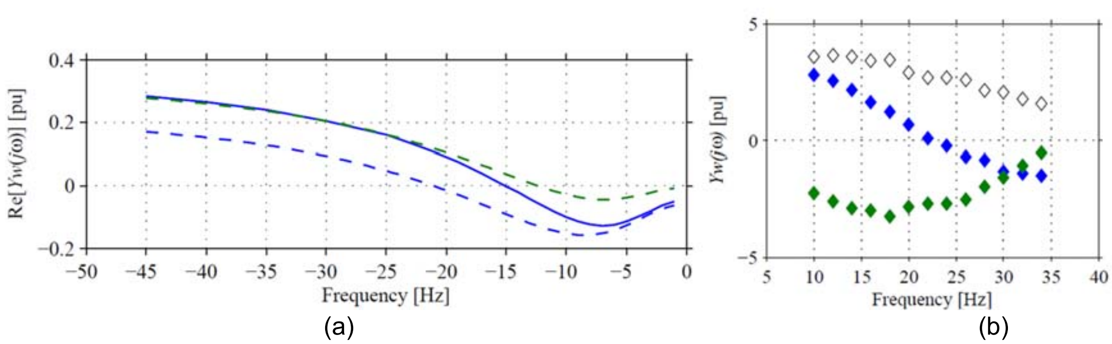


Figure 7 (a) real part of the admittance given by analytical model (dashed) and simulation model (solid).)
(b) measured at Big Glenn by HVDC (blue: real part, green: imaginary part, and white: magnitude of the admittance)

The admittance of the wind turbine system has been calculated using analytical model (dashed curves in Figure 7a) where the system has been evaluated to match the admittance of the simulation model (solid curves in Figure 7b). The admittance has been also measured on the Big Glenn wind turbine by using the VSC-HVDC fully rated testing equipment. The results are shown in Figure 7b.

Both dashed curves in Figure 7a correspond to the evaluation of the mathematical model with slightly different parameters. Observe, however, that the simulation model match with the analytical model. The real part of the admittance of Big Glenn wind turbine is given in Figure 7b in blue curves. The shape follows the admittance of the simulated models. Positive value of the real part of the admittance means that the system was passive against a distribution at that frequency. In other words, the system behaved as a resistor, dissipating the energy of the oscillation. Negative real part means that the system behaved as a current source and that was giving energy into the system.

Although the magnitude was quite different between Big Glenn and the simulation models, this example showed that with the proposed methodology it was possible to retrieve the admittance of the generating unit. Note that here Big Glenn was treated as a black box, meaning that there was no information about the control strategy on the actual wind turbine, while the simulated wind turbine included common current control and grid synchronization strategies given in the literature. These results could be of use in a second stage where the stability of the system constituted by wind turbines and the grid is evaluated. Especially if the frequency scan is performed on an actual wind turbine, such as Big Glenn.

Other test carried out on Big Glenn was testing for voltage dip. During this test, the voltage was reduced to 0.7 pu for 200 ms. From the voltage waveform given in Figure 8a, it was possible to observe that the HVDC controld the applied voltage in a smooth way. At the moment of the dip, the wind turbine reacted by injecting reactive power into the grid, as seen from the green curves in Figure 8c. The test was carried out on a non-windy day, therefore the active power (blue curve in figure) was set to 0 pu. As soon as the voltage was restored, the wind turbine brought back the reactive power to its pre-fault set point. This example demonstrated the use of the investigated testing equipment in evaluating the behaviour of the wind turbine against voltage dip.

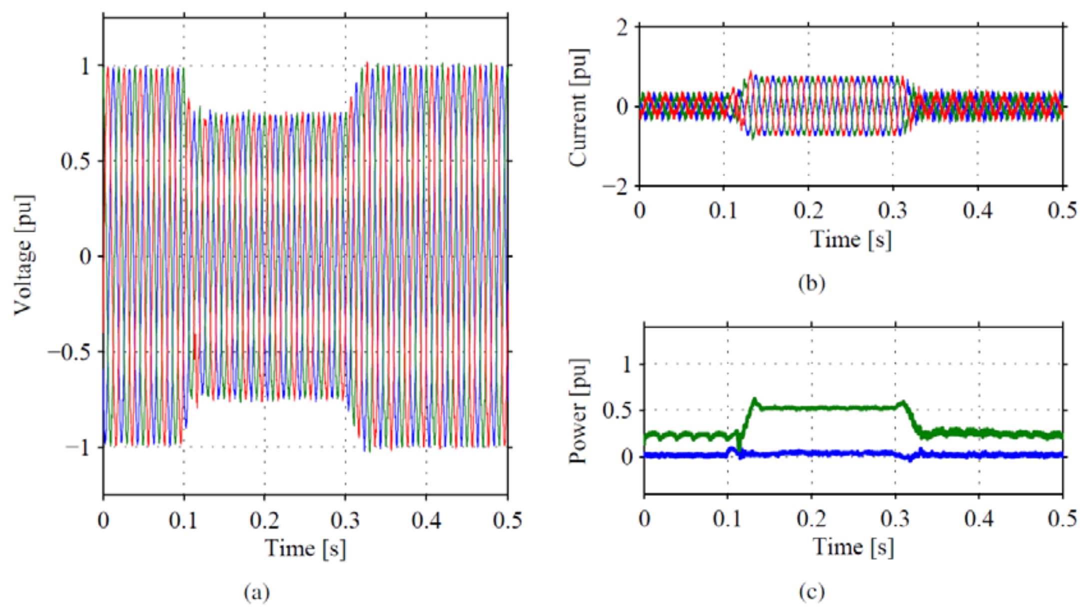


Figure 8 Wind turbine under voltage dip test at low power production. Plot (a): three-phase voltage; Plot (b): three-phase current; Plot (c): active (blue) and reactive (green) power.

Other grid-support capabilities of the wind turbine could also be tested. For example, by varying the applied frequency away from the 50 Hz nominal value, it was possible to test frequency support and active power curtailment properties of the generating unit. Here, by using the HVDC station, the frequency was varied upwards by applying two consecutive frequency swells of 1 Hz. The frequency, shown in Figure 9 in the upper plot was initially controlled at 50 Hz and varied upwards with a ramp of 0.05 Hz/s, or 20 seconds per varied Hz. A frequency of 51 Hz was maintained for 25 seconds approximately. Afterwards, frequency was increased to 52 Hz. The reaction of the wind turbine can be seen in Figure 9 in the lower plots, where the blue curves correspond to the active power production and the green curves shows the reactive power set-point, during the moment of the test.

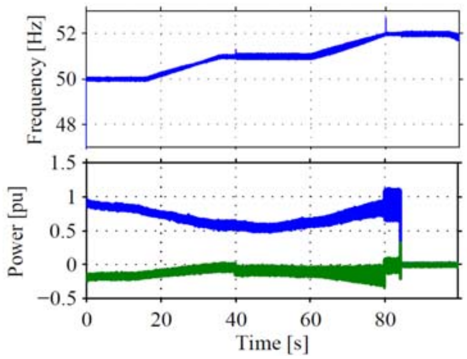


Figure 9 Frequency variation test consisting of two consecutive frequency swells of 1 Hz (top), and active (blue) and reactive (red) power out of the wind turbine (bottom).

Observe in the lower plot that the upwards and downwards tendency of the output power suggest that the wind turbine was varying its operating point according to the wind speed and not in demand of the applied frequency. In addition, the active power is slightly increased 10 seconds after the frequency reaches 51 Hz, at 40 s, while continues to increase with the increasing of the system frequency at 60 s. Finally, a critical point is encountered at 80 s when the frequency reaches 52 Hz. The wind turbine enters into an operation mode that affects the active power output while experiencing an oscillation at 104 Hz. The wind turbine shuts down by an over-frequency protection relay, 5 seconds after the frequency reaches 52 Hz, at t =85 s. The different power production levels experienced when performing the test were also somewhat reflected on the reactive power output of the wind turbine, as seen in green traces in the lower plot.

During second half of 2015, the Licentiate degree has been achieved. The Phd defense was carried out the 15th of December 2016. The new results included frequency characterization of wind turbine to detect possible control interaction between wind turbine and the interconnecting system i.e.: HVDC or AC collector grid, and testing of the generating unit for different scenarios for both normal and faulty condition of the grid. The results have been verified by simulation and laboratory experiment and validated through field test results.

Fulfilment of SWPTC's goals

The Centre's objectives fulfilled by this project were the following:

- 8 doctoral theses (1 in 2015, 4 in 2016, 2 in 2017 and 1 in 2018): This is one of the thesis during 2016.
- Develop electric power technology in wind energy so that cost-effective production of electricity can be developed. The results in the thesis suggest a test method using electric power technology for grid code testing of wind turbines.
- Develop models of relevant electrical systems adapted for simulation of drivetrain and the entire wind turbine. The results in the thesis shows models of electrical system suitable for grid code testing simulations.
- Adapt models to different operating conditions: normal operation, fault operation, turbine faults, electrical grid faults. The results in the thesis shows methods for testing of wind turbines operation during electrical grid faults operation.
- To clarify how utility companies' grid codes influence construction of the electrical system and turbine. The results in the thesis shows how the electrical converter control can be designed to fulfil the grid code requirements, and to a minor extent the electrical system components design, i.e. crowbar operation.
- Swedish development and production of subsystems. The results in the thesis shows clearly how a system for grid code testing by voltage source converter can been designed.

Deviations from project plan

There were no deviations according to the project plan.

Publications

Doctoral thesis

N. Espinoza, *Wind Turbine Characterization by Voltage Source Converter Based Test Equipment,* PhD-Thesis, Chalmers University of Technology, December, 2016

Journal papers

N. Espinoza, M. Bongiorno, O. Carlson, *Novel LVRT Testing Method for Wind Turbines Using Flexible VSC Technology*, in Sustainable Energy, IEEE Transactions in vol.6, no.3, pp.1140-1149, July 2015

Conference papers

N. Espinoza, M. Bongiorno and O. Carlson, *Frequency Characterization of Type-IV Wind Turbine Systems,* in 2016 IEEE Energy Conversion Congress and Exposition (ECCE), Milwaukee, WI, 2016O. Carlson, N. Espinoza, *Grid code testing by Voltage Source Converter*, Wind Energy Science Conference 2017, Technical University of Denmark, Lyngby Campus, 26 - 29 June 2017

Submitted papers

N. Espinoza, O. Carlson, *Field-Test of Wind Turbine by Voltage Source Converter,* submitted to Journal of Wind Energy Science

External activities

Project title	Electromagnetic Transient study of wind farms connected by HVDC
Project number	TG1-21
Organisation	Chalmers University of Technology, Electric Power Engineering
Project leader	Massimo Bongiorno
Other participants	Mebtu Beza (Postdoc)
Report for	2015-10-01 – 2017-09-30
Participating companies	ABB, MVOW, Svenska kraftnät, Vattenfall

Project description

An increasing amount of remote large-scale offshore wind farms are being connected to the main onshore grid by means of high-voltage direct current (HVDC) systems. The remote sites enable good wind conditions, generation out-of-sight and fair construction conditions for wind turbines. However, the complex interaction between the interfaces of the wind turbine generators (WTG) and in particular their converter controls, the cable systems, the offshore substation components and offshore HVDC converter can give rise to harmonic and resonance phenomena as well as in-proper control or protection actions. Both HVDC manufacturers and WTG manufacturers have a principal interest in assuring that their respective equipment and designs are compatible with the electrical infrastructure of wind power plants, both on- and off-shore. Hence, the operation of the wind turbines, the wind power plant controllers and the HVDC Voltage Source Converter (VSC) station control require investigation in order to ensure a good power quality and at the same time to avoid over-engineering costs.

The overall objective with this study was therefore to safeguard the robustness and reliability of future investments in large-scale integration of wind power generation connected to the main grid by HVDC through analytical investigation and the development of relevant simulation models. Furthermore, the project aimed to increase and broaden the knowledge base and competence in the field of electromagnetic transient behaviour, voltage stability and harmonics/resonances of HVDC connected wind farms. More specifically, the study had the objective to:

- Obtain insight into harmonic susceptibility and emission characteristics of relevant equipment in WTG, HVDC system and the ac collection network.
- Obtain representative simulation models of relevant equipment, adequate for case studies and phenomena of interest.
- Perform in-depth analysis of interaction between the HVDC converter control and the wind turbine converter control in order to identify root causes of potential oscillations.
- Investigate possible impacts on the onshore ac grid when oscillatory interactions arise between the offshore HVDC station and the wind turbine converter controls.
- Define key parameters and make sensitivity analysis with respect to stability and robustness of the system.
- Develop mitigation methods such as design guidelines and control strategies to avoid potential resonant phenomena in future.
- Perform a list of case studies, including variations in operating points, number of turbines, feeder cables and control parameters.

The investigated system is similar to the one depicted in Figure 10, where the wind turbines are equipped with Full Power Converters (FPC) and the HVDC converters are based on a modular multilevel converter (MMC). An offshore wind farm with a 66 kV collection cable system with a base power of 400 MW has been considered for the investigation. The dc-link voltage of the HVDC system was 300 kV and 8 MW wind turbines equipped with 0.69/66 kV step-up transformers have been selected for the study.

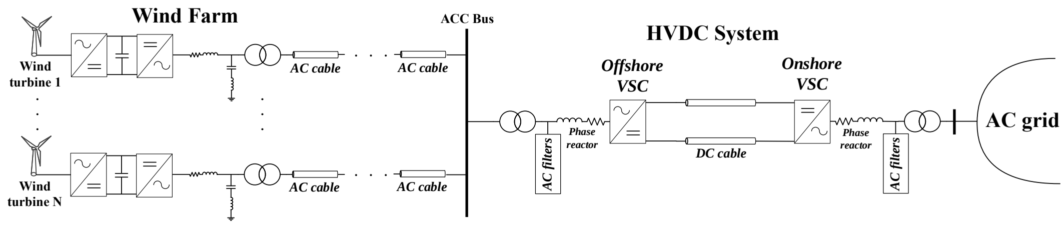


Figure 10 Schematic of the offshore wind farm connected to the onshore grid through HVDC system.

To do the investigation, frequency-dependent impedance models were derived on the ac side based on the various control structures for the wind turbine and HVDC converters. Using the impedance models of the converters together with the impedance of the offshore ac grid, stability of the system could be investigated. The frequency-based stability tool was useful as it does not require full knowledge of the control system for each converter but instead its frequency characteristics. Moreover, frequency-dependent parameters as well as time delays could be accurately represented in the models. The method also provided a useful tool to identify contribution of different system components in the stability of the interconnected system.

Results

In order to achieve the project goals, the study on the stability of offshore wind farm connected by MMC-based HVDC system has produced the following results.

- A frequency-dependent impedance model of A FPC-based wind turbine with an inner current controller and various outer loop controllers has been derived. The derived impedance models were verified against a time domain switching PSCAD model.
- The input impedance of an MMC both with ac-side open-loop and closed-loop operation has been derived. The derived impedance models were verified against a time domain switching PSCAD model.
- The stability of an aggregate model of a 400 MW wind farm connected by an HVDC system with a total dc-link voltage of 300 kV has been investigated. In the aggregate model, the wind farm was represented with the grid-side converter with a variable input power on the dc side, whereas the HVDC system was represented by the offshore converter with a constant dc-link voltage. The offshore ac network was represented by transformers, filters and a single 66 kV ac cable model. Using a frequency domain approach, it has been shown that the stability of the aggregate system could be predicted. It was demonstrated that the nature of resonances observed were dependent on the operating points, the selection of the controller parameters and the available passive components.
- In the studied wind farm - HVDC system, the wind farm was represented with the grid-side converter with a variable input power on the dc side, whereas the HVDC system was represented by the offshore converter with a constant dc-link voltage. The impacts of the simplification in the system representation (such as aggregation, the onshore VSC station, the wind turbine system) were investigated.
- The impact on stability of both open- and closed-loop control approaches for the offshore MMC has been investigated.
- Method of aggregating multiple turbines in a wind farm system has been developed. The impact of the aggregation in the system stability study has been investigated.
- Possible sources of unstable resonances in a wind-farm HVDC system such as converter control parameters and nature of passive components has been identified and possible solutions has been suggested.
- The impact of offshore oscillatory oscillations on the onshore ac grid has been investigated.
- The impact of alternative control strategies for the FPC-based wind turbine (control structures without PLL such as alpha-beta control, virtual-machine control, and power-synchronization control) on stability of the wind-farm HVDC system has been investigated.

Fulfilment of SWPTC's goals

The aim of this project was to ensure the robustness and stability of offshore wind farms connected to the onshore grid though HVDC. In addition to increasing the knowledge base and the competence in the field of electromagnetic transient behaviours in Chalmers, the project results helped the relevant industries to avoid unnecessary investments related to the investigated phenomena. In addition, one of the SWPTC's goals focuses on wind farm collection grid and possible issues that might arise in case of the use of DC technology and thereby high penetration of power electronic controllers. This has been fulfilled with in this project, by investigating causes of system failures and suggesting possible solutions in a wind farm – HVDC system.

Deviations from project plan

No major deviations from the project plan.

Publications

Journal papers

M. Beza, M. Bongiorno, G. Stamatiou, L. Harnefors, *Analytical Derivation of the AC-Side Input Admittance of a Modular Multilevel Converter With Open- and Closed-Loop Control Strategies*, IEEE trans. Power Del., May 2017

Conference papers

M. Beza, M. Bongiorno, *Stability of grid-connected modular multilevel converter with open- and closed-loop ac-side control*, European Conference on Power Electronics and Applications, Sept. 2017

Submitted papers

M. Beza and M. Bongiorno, *Identification of resonance interactions in offshore-wind farms connected to the main grid by MMC-based HVDC system*, International Journal of Electrical Power and Energy Systems (under second round of review), 2018

External activities

There has been a close cooperation with the participating companies (ABB, Vattern fall, Svenska Kraftnät and Mitsubishi Vestas Offshore Wind) during this period. Parameters for the various models have been suggested and comments on the project progress have been provided through three reference group meetings at Chalmers. A one week research visit to Vestas also took place for model verification.

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	2014-10-01 – 2016-09-30
Participating companies	

Project description

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 were used.

A time-marching vortex lattice free wake (VLFW) based on the incompressible, inviscid and irrotational flow has been developed to study the aerodynamic loads. It was based on the potential flow where it was 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 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.

A new module has been added to take unsteady incoming flow into account using either a time series of turbulent wind field, generated by Large-Eddy Simulation, or Taylor's hypothesis (Frozen turbulence), provided by spectral model. This has been done in cooperation with the project Fatigue Loads in Forest Regions (TG2-2) generating turbulent fluctuations in atmospheric boundary layers both with and without forest.

Results

The effect of the skewed wake, due to the yaw misalignment, on the wake aerodynamics of wind turbine has been studied using the VLFW method. The results were compared with the MEXICO wind tunnel measurements where there was a quite good agreement between the simulation and experimental data. Particularly, it has been found that in addition to power reduction of the wind turbine due to the yawed flow, there was a periodic load variation along the rotor blade which accordingly increases the fatigue load.

Furthermore, three different methods called the standard potential method, the 2D static airfoil data method and the dynamic stall method have been introduced to calculate the aerodynamic loads. The results were compared with the MEXICO experiment, the BEM method and the GENUVP code. It was shown that for more accurate load and power prediction, coupling to the 2D static airfoil data was necessary even though some complex conditions such as separated flow, stall condition and centrifugal forces cannot be well predicted. For the non-yawed flow, considerable discrepancies between the VLFW simulations and measurement data close to the blade root (inboard sections) may be physically explained due to the thick airfoil profiles which consequently resulted in the flow separation and stall condition even if at lower wind velocities. This was also certified for the NREL 5-MW machine. For the yawed flow, the difference between the maximum peak position of the normal forces along the rotor blade induced an additional moment on the rotor due to the yaw misalignment. Additionally, for almost all spanwise sections, the simulation presented a phase shift against the experiments for both the normal and tangential forces, nevertheless it predicted the azimuthal load variation rather well.

To predict the load and wake evolution under the realistic flow field around the wind turbine, in cooperation with TG2-2, time-dependent turbulent inflow fields (generated by LES and spectral model for both non-forest and forest regions) have been used as input data for the developed vortex method in-house code. The results showed that presence of forest canopies decreased the mean power, and increased the standard deviation of the fluctuating power production. This certified dependency of the inflow turbulence intensity and power production of a wind turbine.

Fulfilment of SWPTC's goals

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

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

Deviations from project plan

There was no deviation from the project plan.

Publications

Doctoral thesis

H. Abedi, *Development of Vortex Filament Method for Wind Power Aerodynamics*, PhD thesis in Thermo and Fluid Dynamics, Department of Applied Mechanics, Chalmers University of Technology, Göteborg, 2016

Journal papers

H. Abedi, L. Davidson, S. Voutsinas, *Enhancement of free vortex filament method for aerodynamic loads on rotor blades,* Journal of Solar Energy Engineering, Transactions of the ASME, Vol. 139 Nummer/häfte 3 s. Article number 031007, 2017

Conference papers

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, 14-20 November 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.

H. Abedi, L. Davidson, S. Voutsinas, *Development of free vortex wake model for wind turbine wake aerodynamics under yaw condition*, 34th Wind Energy Symposium, 4-8 January 2016 San Diego, USA.

Submitted papers

H. Abedi, L. Davidson, S. Voutsinas, The impact of wind field generation methods on wind turbine power production using Free Vortex Wake Method, Journal of Wind Energy (under submission process), 2016-2018

External activities

- Visiting National Technical University of Athens (NTUA), from 09-Mar to 03-Apr 2015, Athens, Greece
- Project presentation, Vindkraftsforskning i fokus konferens, 6-7 October 2015, Uppsala, Sweden
- The Science of Making Torque from Wind (TORQUE 2016), 5-7 October 2016, Munich, Germany

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	2014-10-01 – 2015-09-30
Participating companies	Göteborg Energi

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 characterized by strong wind shear and strong turbulence, which induce high aerodynamic loads on the wind turbines. In turn, the increased loads lead to shorter maintenance intervals and shorten the wind turbines fatigue life.

The present project aimed at using CFD for the prediction of the atmospheric boundary layer (ABL) under the direct influence of a forest. Both wind shear and turbulence were inherent in the flow solution and could be stored in a database for subsequent use as input in load calculations. These load calculations were possible to perform in-house, using the state-of-the-art structural wind turbine simulation tool FAST. Additionally, load calculations could 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 were available.

Results

Numerous Large-Eddy Simulations (LES) of the wind flow over forests have been performed. Even from the rather coarse simulations, good agreement with measurement data was obtained.

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 has been submitted for publication.

Cooperation with the project “TG2-1: Aerodynamic loads on rotor blades” has been carried out. Atmospheric turbulence from Large-Eddy simulations has been supplied for the use in that project.

During the extended visit to Northeastern University in Boston, a reduced order model of the NREL 5MW standard wind turbine had been 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 were 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

Doctoral thesis

B. Nebenführ, *Turbulence-resolving simulations for engineering applications*, Doctoral thesis, Chalmers University of Technology, September 2015

Journal papers

B. Nebenführ and L. Davidson, *Large-Eddy Simulation Study of Thermally Stratified Canopy Flow*, Boundary-Layer Meteorology, August 2015, Volume 156, Issue 2, pp 253-276

B. Nebenführ and L. Davidson, *Prediction of wind-turbine fatigue loads in forest regions based on turbulent LES inflow fields*, Wind Energy. Vol. 20 (6), p. 1003-1015, 2017

External activities

No external activities were done during this period.

Project title	Triblade rotor blades, preparatory project
Project number	TG2-21
Organisation	Winfoor AB
Project leader	Rikad Berthilsson
Other participants	Chalmers
Report for	2015-07-01 – 2016-03-27
Participating companies	Marström Composite

Project description

In this preparatory project the Triblade technology have analysed and planned for a subsequent R&D project to be run within SWPTC.
The preparatory project tasks are

1. Analyse the possibility to run a R&D project for Triblade within SWPTC. Identify interested consortium partners.
2. Define the scope for the R&D project: Fluid mechanics in 2D and 3D, noise, vibrations, turbulence, optimization, structural analysis, dimensioning and design of members and joints, hub connection, static and dynamic loads, buckling, fatigue, production development, prototyping, wind tunnel tests, pilot installation, literature studies.
3. Perform initial studies on selected tasks, run wind tunnel tests on existing prototype, analyze possible production techniques, prototyping cost estimation.
4. Complete a proposal for the R&D project: resources, budget, time plan, work packages, deliverables, and goals.

Results

All tasks of the preparatory project have been completed. A draft proposal for an R&D project has been written. The consortium partners would be Winfoor and the fluid mechanics divison at Chalmers. It has however proven to be difficult to find an acceptable setup of the project such that it can be co-financed by SWPTC.

Within the preparatory project we have done initial studies of the aerodynamic and structural properties of Triblade through CAD modelling and FEM simulations. We have also done initial studies on production development. The structural analysis includes analysis of buckling, stress concentration, and vibrations. The aerodynamic analysis was carried in the software Openfoam and is so far limited to static 2D analysis only. As a result, a draft model for Chalmers test wind turbine at Hönö has been completed and analysed.

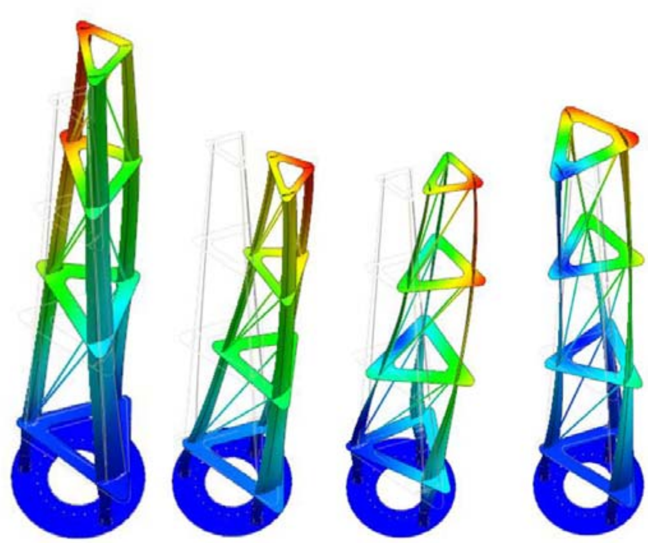


Figure 11 The first four buckling modes of Triblade for Chalmers test turbine.

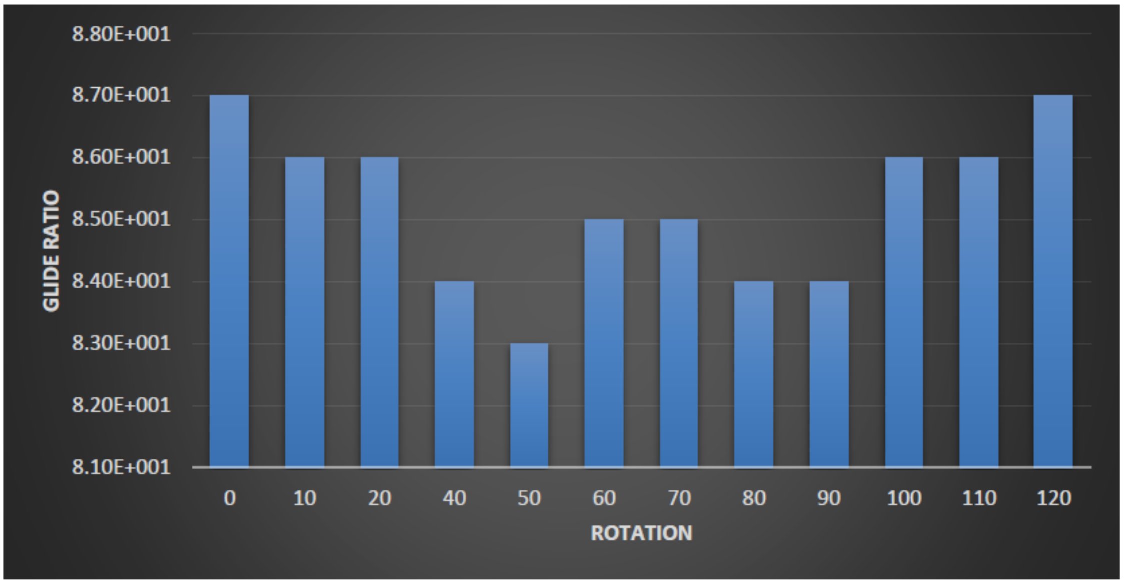


Figure 12 Glide ratio of Triblade as a function of the angle between the three blade configuration of Triblade and the relative wind direction.

Figure 12 shows that the glide ratio changes only marginally with the relative wind direction.

A wind tunnel test was done at Chalmers wind tunnel. A model of a section of a Triblade that has previously been tested at the wind tunnel was tested again but with a different method. The test showed that the diagonal struts affects the flow of the air significantly, especially at the middle of the model where the struts cross each other. The conclusion was that thinner and as few struts as possible should be used. For additional wind tunnel tests, a smaller model should be considered due to boundary effects from the close proximity between the model and the wind tunnel walls.

A prototype of a joint between two sections of a blade was made by Marström. The prototype uses a telescopic connection for joining the blades which has been analysed and tested for loads. The telescopic concept for joining blade parts shows promising results and has potential for a modular design of Triblade that can be manufactured and transported in section for later assembly.

Outside the scope of the preparatory project, a pilot installation has been completed. For the pilot a rotor comprising three 3.6 m long Triblades have been manufactured. The rotor diameter is 7.4 m and it has been installed and tested at Nordic Folkecenter in Denmark. A video of the test can be found at https://vimeo.com/154300292 using the password: greenpower. The power output of this first pilot is in accordance with expectations, peaking at 8.5 kW at 13 m/s.

Fulfilment of SWPTC's goals

The preparatory project and subsequent R&D project will contribute to

- Lowering mass of rotor blades.
- Increase the performance of wind turbine
- Increase knowledge on wind turbine components and systems

Deviations from project plan

The preparatory project was completed behind time schedule, but otherwise according to plan.

Publications

None

External activities

None

Project title	Wind power in forest – the effects of clearings
Project number	TG2-22
Organisation	Chalmers University of Technology, Fluid Dynamics Division
Project leader	Professor Lars Davidson
Other participants	Johanna Matsfelt (PhD student)
Report for	2016-10-01 – 2018-09-30
Participating companies	Meventus, Stena Renewable

Project description

The wind flow over forested terrain is characterized by a slow down in wind speeds, higher wind shear and increased turbulence. These are factors that increase fatigue loads on turbines, and most wind turbines today are not designed for these loads. This leads to higher maintenance costs and a decrease in overall life time. This project investigated how forest clearings impact the wind conditions in a wind farm. The aim was to learn more about the effects of clearing forest around a wind turbine to increase production and minimize loads. The study covered the effect of larger clearings. In the project LIDAR scanning and advanced CFD modelling have been used to provide recommendations on how and when to clear forest around wind farms and wind turbines. The CFD tool SOWFA (Simulation fOr Wind Farm Application) developed by NREL have been further developed. SOWFA is OpenFOAM coupled to the aeroelastic solver FAST developed by NREL. This is done using ALM (Actuator Line Model). The ABL (Atmospheric Boundary Layer) was here simulated using LES (Large Eddy Simulation).

Results

SOWFA was further developed by implementing a drag and heat source term to represent the forest. The Ryningsnäs setup was simulated with homogenous forest, with the current clearing and with an extend clearing. The flow field was investigated, and the results obtained from FAST was evaluated. To obtain the fatigue loads the Rainflow counting algorithm has been applied to the load history of the data obtained from FAST.

It was found that the shortest recommended length for a precursor in SOWFA was too short because streaks occurred. The length needed to have a streak free precursor was found to be more than 3 times the length of the recommended. This streak free precursor was then used as inlet for the simulations.

Atmospheric boundary layer simulations showed that the current clearing could be used to turn the flow field. One dimensional momentum theory used on the atmospheric boundary layer simulations showed the same trends but different magnitudes except for the second wind turbine in the extended clearing. For this wind turbine the one dimensional momentum theory showed that the electrical generator power was higher than in the homogeneous forest but FAST show a decrease. This show the complexity of the problem and the importance of using FAST. The extended clearing showed the lowest average and fatigue loads of the bending moment around the y-axis. More research is needed to find the optimal clearing and location of the wind turbines in relation to it to both increase the electrical generator power and decrease the loads.

Fulfilment of SWPTC's goals

The project has lead to increased knowledge of wind power in forest regions, and how clearings effect the fatigue loads and maintenance costs of wind turbines. The project has contributed to the following goals:

- Lead to an increased life time of wind turbines (optimized wind power in forest regions)
- Better prediction of fatigue loads in forest regions. The project will lead to a total weight loss (because of more accurate load predictions, the safety margin can be reduced)
- Better understanding of how different forest clearings impact wind turbine fatigue loads

Deviations from project plan

As validation study and first setup Ryningsnäs was used. Here the flow field was investigated both with and without turbines. To avoid the second wind turbine behind the clearing being affected by the wake of the first wind turbine on the side of the clearing, simulations with only wind turbine two was ran. Simulations with homogenous forest, the current clearing and an extended clearing was evaluated to be able to isolate changes. The wind turbines were also investigate using the results from FAST.

Publications

No publications.

External activities

- Attendance, The Science of Making Torque from Wind (TORQUE 2016), 5-7 October 2016, Munich, Germany.
- Presentation, “Wind power in forest – The effects of clearings”, Vindkraftforskning i fokus 2017, 3-4 April 2017, Gothenburg, Sweden.
- Presentation, “Influence of generated wind field on Wind-turbine power production in forest Region”, Wind Energy Science Conference 2017, 26-29 June 2017, Copenhagen, Denmark.
- Presentation, “Inverkan av gläntor i skog”, Energimyndigheten Energivärlden tema vind, 29-30 May 2018, Stockholm, Sweden.
- Presentation, “Large-eddy simulation study of effects of clearing in forest on wind turbines”, OpenFOAM Wind power, 13-15 June 2018, Visby, Sweden.

Project title	Wind turbine drive train system dynamics
Project number	TG3-1
Organisation	Chalmers University of Technology, Applied Mechanics
Project leader	Viktor Berbyuk
Other participants	Saeed Asadi (PhD student: March 2013-March 2016), Håkan Johansson, Jan Möller
Report for	2014-10-01 – 2016-03-31
Participating companies	

Project description

The dynamics of wind turbines is complex and a critical area of study for the wind industry. The multidisciplinary nature of wind turbine design adds to the complexity of this task, as the subsystems of a wind turbine need to be tuned with respect to a common objective to achieve a cost effective and optimum structural performance. The project is a continuation of the since March 2013 running Ph.D. project having as a main focus drive train system dynamics of wind turbines. The drive train system is here considered as the electro-mechanical subsystem comprising shafts, bearings, gearbox, shaft couplings, mounts, generator, and other functional components of a wind turbine that transfers mechanical power from the rotor hub to the electric power generator, and thereby plays an important role in wind turbine dynamics. The project included both theoretical and experimental study of drive train system dynamics. It focussed on the high-speed shaft subsystem of indirect drive wind turbines and interaction between functional components and system dynamic response, faults modelling and detectability of defects in bearings in wind turbine drive trains.

Results

The mathematical and computational models of high speed shaft subsystem of wind turbine drive train have been developed by using Lagrangian formalism. The test rig of high speed shaft drive train was built, instrumented with SKF WindCon 3.0 condition monitoring system and used for experimentally study system vibration dynamics and load distribution. More details about the developed test rig are available in papers. By using the obtained measurement data, the developed mathematical and computational models have gone through model validation process by qualitative comparison of simulation and experimental data. Then the system kinematic and dynamic responses were studied for different operational scenarios and system structural parameters (ratio of shaft bending stiffness and stiffness of mounting structures, unevenly inertia load distribution, others).

The dynamics of torsional vibrations and transient events which can reduce fatigue life of functional components of a wind turbine drive train high speed subsystem was studied both by modelling and experiments. The system dynamic response was studied for different operational scenarios and structural parameters (transient-steady state-shut down cycle with and without eccentric mass, others). A simplistic motor model with slip and torque ripples was used within the system modelling. This gave an insight in how faults sources can contribute to the system dynamics of drive trains. The results also indicated that the current drive train system modelling could be decomposed into two main simpler subsystems focusing on torsional and bending drive train flexibilities separately.

Based on Multiplicative Dimensional Reduction Method, the global sensitivity analysis of high speed shaft drive train of wind turbine with respect to input structural parameters has been considered as one of the key stages of drive train system design. The variance based global sensitivity indices were introduced and the Gaussian quadrature integrals were employed to evaluate the contribution of input structural parameters correlated to the objective functions. For each operational scenario, the most effective parameters have been recognized for high speed shaft drive train. The primary and total sensitivities of the objective functions were examined with respect to each input parameter.

A reliable and computationally efficient algorithm has been developed for the global sensitivity analysis, which gives a beneficial insight into solving different optimization and design problems of wind turbines. It was shown that global sensitivity analysis results obtained can reduce the costs associated with a wind turbine design by significantly narrowing down the number of the design parameters to be used for optimization problems of a wind turbine drive train components.

Dynamic modelling and vibration simulation are important for fault mechanism studies to provide proofs for defect detection and fault diagnose. In this regard, it has been demonstrated that the proposed models of high speed shaft subsystem of a drive train could be used within global sensitivity analysis in order to investigate the detectability of faults in different components. By introducing defects in drive train functional components and investigating sensitivity indices, detectability of faults by global sensitivity analysis was proved. The results showed that the proposed methodology was capable of detecting damage in the functional components such as bearings in early stage before a complete failure. The application of this methodology within the detection, prediction, and prevention framework has a potential to reduce the maintenance cost for critical components. The results can also provide a better understanding and useful hints in wind turbine drive train system dynamics with respect to different structural parameters, ultimately designing more efficient drive trains.

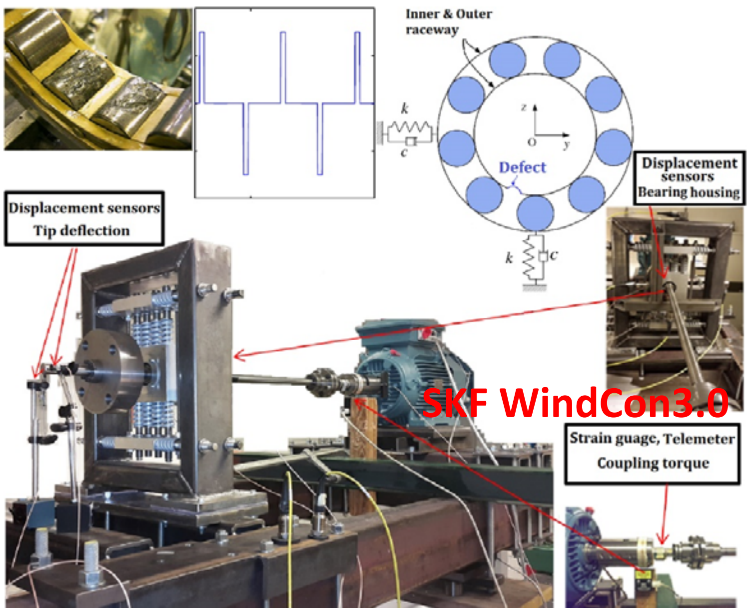


Figure 13 The test rig of high speed subsystem of a drive train of a wind turbine

Publications

Licentiate thesis

S. Asadi, *Drive Train System Dynamics Analysis*: *Application to Wind Turbines,* Thesis for the degree of Licentiate of Engineering, 2016:01, ISSN 1652-8565, Department of Applied Mechanics, Chalmers University of Technology, Göteborg, Sweden

Journal papers

S. Struggl, V. Berbyuk, H. Johansson, *Review on wind turbines with focus on drive train system dynamics*, *Wind Energy*, Vol. 18, 4, p. 567-590, 2015 http://dx.doi.org/10.1002/we.1721

Conference papers

S. Asadi, V. Berbyuk, H. Johansson, *Vibration dynamics of a wind turbine drive train high speed subsystem: Modeling and validation*, Proceedings of the ASME 2015 International Design Engineering Technical Conferences and Computers & Information in Engineering Conference IDETC/CIE**,** August 2-5, 2015, Boston, Massachusetts, USA, paper DETC2015-46016, http://dx.doi.org/10.1115/DETC2015-46016

S. Asadi, V. Berbyuk, H. Johansson, *Structural dynamics of a wind turbine drive train high speed subsystem: Mathematical modeling and validation*, In Proc. of the International Conference on Engineering Vibratio*n,* Ljubljana, 7 - 10 September; [editors Miha Boltežar, Janko Slavič, Marian Wiercigroch]. - EBook. - Ljubljana: Faculty for Mechanical Engineering, 2015 p. 553-562

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

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, A. Eriksson, A. Kulachenko, M. Mihaescu and G. Tibert (Eds.), KTH, Stockholm, 2014

Master thesis

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

External activities

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

Project title	Development of Compound Bearing Concept for Wind Power Applications
Project number	TG3-2
Organisation	Swerea
Project leader	Sven Haglund
Other participants	Hans Kristoffersen, Ingemar Strandell
Report for	2014-10-01 – 2014-12-31
Participating companies	SKF, Erasteel, Bodycote

Project description

The aim of the project was 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 was 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.

This project was a continuation of a project run within SWPTC stage 1.

Results

Equilibrium and kinetic simulations were carried out with three raceway materials in combination with nine different raceway materials. The most promising combinations has 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.

The contact fatigue properties were evaluated for the M50 material. The performance was increased compared to standard bearing materials. The steel matrix is stronger and fewer defects. The results were promising and it were recommended to continue the test with the larger compound rings having M50 in the case.

Demonstrator compound washers has successfully been manufactured in the combinations M50 (raceway) // SS2244 (core) and XD15NW (raceway) / Ovako225A (core). The core materials were cast and subsequently turned into blanks. The blanks were put in steel containers and surface materials (metal powders) were filled into the containers. The containers were HIPed at 1150°C. The washers where soft annealed and soft turned prior to hardening. The bonding between the core and surface materials were strong and no heat treatment cracks were found.

Fulfilment of SWPTC's goals

The project has been successful. It has been shown that bearings can be produced by the suggested route and that the raceway material tested has better fatigue properties. Continued development and testing must be performed before compound bearings can be mounted in wind turbines. Therefore, it is probably too early to say whether or not this project will fulfil some of SWPTC´s goals. However, if compound bearings reach production stage it will have helped to solve a major problem for the industry giving Swedish companies a competitive edge. This leads to new jobs within the manufacturing industry.

Deviations from project plan

The project was late compared to the original time plan. The manufacturing of the fatigue test rings, the fatigue tests and the manufacturing of the demonstrator washers took unexpectedly long time. The manufacturing of the fatigue test rings were approximately 6 months late. However the project has now been finished and a final report has been written.

Publications

No publications were generated during this period.

External activities

No external activities were done during this period.

Project title	FreeDyn and wind turbine system simulation
Project number	TG3-21
Organisation	Chalmers University of Technology, Applied Mechanics
Project leader	Håkan Johansson
Other participants	
Report for	2014-10-01 – 2015-01-31
Participating companies	

Project description
To carry out system simulations and to support other SWPTC projects, a framework for such a tool called FreeDyn has been developed in earlier TG3-1 project. Now, the work is directed towards filling this framework with actual components models, which requires additional developments. This project focused on the drivetrain component and the control system to support verification and testing of the code, a Matlab version of FreeDyn was to be developed.

Results
Drive train model and a control model was implemented. A Matlab model for wind turbine simulation was developed. However, during the project it was discovered that the new version of FAST would fulfil the Centre's criteria for a simulation tool. Therefore, further work on FreeDyn was stopped.

Fulfilment of SWPTC's goals
The project addresses the common goal of the SWTPC to build up knowledge on wind turbine systems by better understanding of system simulations which are central tools for the understanding and analysis of wind turbines. A wind turbine is not specific by its components per se, but rather how these components interact to constitute a complete wind turbine. Hence, system simulation is key to predict how a specific component affect the whole turbine, and how the turbine affect the specific component.

Deviations from project plan
The implementations in FreeDyn has not undergone the more careful testing that should be done if to be put in a public release.

Publications
A draft for FreeDyn Appendix regarding co-rotational formulation for beam elements has been written, but is not published.

External activities
No external activities have been undertaken.

Project title	Modeling drive train dynamics from online measurement data
Project number	TG3-22
Organisation	Chalmers University of Technology, Mechanics and Maritime Sciences
Project leader	Håkan Johansson
Other participants	Saeed Asadi (PhD student)
Report for	2016-10-01 – 2018-03-31
Participating companies	

Project description

The goal of this project is to investigate how SCADA and other sensors can be used to predict drive train dynamics during operation and its implication on drive train components' fatigue life for direct as well as indirect drive turbines. The main activities include developing drive train models using multibody dynamics formulation, validate this model using existing test rig in lab as well as existing wind turbine system simulation tools for direct and indirect turbines. Global sensitivity analysis will be used to quantify dynamic behaviour with respect to different input parameters, as well as the influence of sensor data on fatigue loads on drive train components (main bearings and gearbox).

Results

The overall expected result from this project is an increased understanding on how different operation conditions affect turbine drive train dynamics; a model that can be used to evaluate measurement data as well as a proposal for suitable sensor placement strategy to determine drive train component loading. All these results can contribute in the work planned for the project proposal "Wind turbines under harsh operation conditions".

The specific results have been achieved to date

- Direct drive train modelling based on multibody dynamics
    - Model verified using ViDyn system simulations
    - Model to predict bearings damage index and main shaft deflection.
    - Evaluate effect from wind speed, turbulence intensity and incoming wind vertical inclination
- Global sensitivity analysis of a direct wind turbine drive train.
    - GSA of direct drive train with respect to structural parameters
    - GSA of direct drive train with respect and excitation wind parameters

The results from Direct drive train modelling based on multibody dynamics revealed a great deal of variability in predicted fatigue life at high wind speeds, although this variability has limited impact since these conditions are quite rare. The effect from vertically inclined wind field showed implied that a big upward vertical component of the wind effected the fatigue life of front main bearing favourably, but reduced fatigue life of rear main bearing.

Many structural parameters are not exactly known, which introduces uncertainty in predicted fatigue life of drive train components. Therefore, global sensitivity analysis was examined to quantify the effect of this uncertainty. The global sensitivity analysis showed which parameters that are most important to know with great precision, in this case bearing location and bearing structural stiffness was the most important. The bearing positions are usually very well known, but their stiffness is not. Furthermore, a global sensitivity study of the hub force components was carried out to investigate their effect on drive train. The wind components associated with wind shear and wind lateral inclination had the largest effect on main bearings fatigue life.

The model for prediction of gearbox motion under operation is useful for future assessment of optical measurement of gearbox motion, which in turn can be an efficient mean to assess wind turbine operation, both for turbines in use and to develop and assess new turbine design.

These results are collected in three papers, two submitted for international publication.

Fulfilment of SWPTC's goals

The project addresses the common goal of the SWTPC to build up knowledge on wind turbine components focusing on high speed bearings and gearbox internal dynamics to facilitate design of optimal wind turbines and their drive train functional components. The modelling and evaluation of different operating conditions is of major value for the ongoing project "Wind turbines under harsh operation conditions".

Deviations from project plan

The validation using test rig has not been done, and is currently not judged necessary as the modelling gives reasonable agreement with existing simulation models.

Publications

Doctoral thesis

S. Asadi, *Wind turbine drive train system dynamics: Multibody dynamic modeling and Global Sensitivity Analysis*, PhD Thesis, Chalmers University of Technology, 2018

Conference papers

S. Asadi, H. Johansson, *Multibody dynamic modelling of a direct wind turbine drive train*, Wind Energy Science Conference 2017, 26-29 June 2017, Copenhagen, Denmark

Journal papers

S. Asadi, V. Berbyuk, H. Johansson, *Global sensitivity analysis of high speed subsystem of a wind turbine drive train*, International journal of Rotating Machinery 2018:1-20, 9674364

Submitted papers

S. Asadi, H. Johansson, *Multibody dynamic modelling of a direct wind turbine drive train*, manuscript of journal paper submitted for publication

S. Asadi, H. Johansson, *Global sensitivity analysis a direct wind turbine drive train,* manuscript of journal paper submitted for publication

S. Asadi, H. Johansson, *Multibody dynamic formulation of a wind turbine indirect drive train with focus on gearbox modeling and motion*, manuscript of journal paper in preparation

External activities

No 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	2014-10-01 – 2015-09-30
Participating companies	

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

The work done during stage 2 of the centre focused on the following three topics:
(1) a novel stochastic FE model updating framework is developed for estimation of the uncertainty in model parameters and predictions from the measured frequency responses. This framework combines the technique of "FE model calibration with damping equalization" with the principles of bootstrapping. The performance of the former is improved in dealing with noisy measurements by: (i) use of a new dedicated frequency sampling strategy that gives the frequencies at which the experimental FRF of the structure needs to be measured, and (ii) use of a weighted log-least-squares objective function. The bootstrapping technique is used to take into account the uncertainties in the measurements and forward simulations in order to quantify the uncertainty in the parameters and to assess their effects on the predictions made by the FE model.
(2) A modal parameter estimation algorithm is developed that satisfies the following criteria: (i) it allows for fast and robust identification of MIMO systems of a given order, (ii) it avoids high dimensional optimization, (iii) it provides uncertainty bounds on the estimated modal parameters, and (iv) it needs no user-specified parameters or thresholds. This algorithm combines the principles of bootstrapping for

uncertainty quantification with the technique of subspace based system identification and also with unsupervised learning algorithms. The key to success of the engaged unsupervised learning algorithm is a novel correlation metric that is able to treat the problems of spatial eigenvector aliasing and non-unique eigenvectors of coalescent modes simultaneously.

(3) Approximate Bayesian computation by subset simulation, ABC-SubSim, is a recently appeared algorithm for Approximation Bayesian Computation (ABC) which exploits the subset simulation for efficient rare-event simulation. The merits of ABC-SubSim stems from the facts that (i) it does not suffer from the curse of dimensionality, and (ii) it bypasses the explicit evaluation of the likelihood function and, as a result, is applicable to any model for which forward simulation is available. One example of such models is a nonlinear state-space model with state and output uncertain prediction errors for which an analytical formula for the likelihood function is difficult to establish. Here, a dynamic problem is formulated in form of a general hierarchical state-space model to show that the ABC-SubSim algorithm is performing an exact Bayesian updating for a new model in which its output is corrupted by a uniform additive error term. This formulation not only allows understanding the quality of the ABC approximations of the posterior distribution and model evidence, but also makes it possible to independently approximate the model evidence for each of the competing models as a simple by-product of the ABC-SubSim algorithm. Therefore, in the case that there exists several competing models to represent a real structure, the model evidence, which is a simple by-product of the ABC-SubSim algorithm, can be used to rank these models.

Outcomes of the aforementioned studies are written in form of five journal papers of which three papers are accepted for publication and two papers are submitted for international publications. Furthermore, the results of these studies were presented in international conferences.

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. However, it is anticipated that work with other partners can fill this gap for the purpose of this project.

Publications

Doctoral thesis

M. K. Vakilzadeh, *Stochastic model updating and model selection with application to structural dynamics*, Doctoral thesis, Göteborg: Chalmers University of Technology, 2016

Journal papers

S. Rahrovani, M. K. Vakilzadeh, T. Abrahamsson, Modal Dominancy Analysis Based on Modal Contribution to Frequency Response Function H_2-norm, *Mechanical Systems and Signal Processing*, 48(1-2), pp. 218-231, 2014

M. K. Vakilzadeh, Y. Huang, J. L. Beck, T. Abrahamsson, *Approximate Bayesian Computation by Subset Simulation Using Hierarchical State-Space Models*, Mechanical Systems and Signal Processing, Available online 4 March 2016, ISSN 0888-3270, http://dx.doi.org/10.1016/j.ymssp.2016.02.024

M. K. Vakilzadeh, V. Yaghoubi, A.T. Johansson, Thomas J.S. Abrahamsson, *Stochastic Finite Element Model Calibration Based on Frequency Responses and Bootstrap Sampling*, Mechanical Systems and Signal Processing. Vol. 88, p. 180-198, 2017

M. K. Vakilzadeh, J.L. Beck, T. Abrahamsson, *Using Approximate Bayesian Computation by Subset Simulation for Efficient Posterior Assessment of Dynamic State-Space Model Classes*, IAM Journal of Scientific Computing. Vol. 40 (1), p. B168-B195, 2018

V. Yaghoubi, M. K. Vakilzadeh, A.T. Johansson, T. Abrahamsson, *Automated Modal Parameter Estimation Using Correlation Analysis and Bootstrap Sampling,* Mechanical Systems and Signal Processing. Vol. 100, p. 289-310, 2018

Conference papers

M. K. Vakilzadeh, V. Yaghoubi, A.T. Johansson, T. Abrahamsson, *Towards an Automatic Modal Parameter Estimation Framework: Mode Clustering*, International Modal Analysis Conference IMAC XXXIII, Florida, USA, February 2-7, 2015

Vahid Yaghoubi, M. K. Vakilzadeh, Thomas J.S. Abrahamsson, *A parallel solution method for structural dynamics response analysis*, IMAC XXXIII, Florida, USA, 2015

M. K. Vakilzadeh, V. Yaghoubi, T. McKelvey, T. Abrahamsson, L. Ljung, *Experiment Design for Improved Frequency Domain Subspace Identification of Continuous-Time Systems*, IFAC, Beijing, China, 2015

M. K. Vakilzadeh, Y. Huang, J. L. Beck, T. Abrahamsson, *Approximate Bayesian Computation by Subset Simulation for Parameter Inference of Dynamical Models*, IMAC XXXIV, Florida, USA, January 25-28, 2016

V. Yaghoubi, M. K. Vakilzadeh, A.T. Johansson, T. Abrahamsson, *Stochastic Finite Element Model Updating by Bootstrapping*, IMAC XXXIV, Florida, USA, January 25-28, 2016

M. K. Vakilzadeh, A. Sjögren, A. T. Johansson, T. Abrahamsson, *Sequential Gauss-Newton MCMC algorithm for high-dimensional Bayesian model updating*, IMAC XXXV, California, USA, Jan. 30-Feb. 2, 2017

External activities

The PhD student participated in a four-month visiting program at California Institute of Technology (Caltech) in which the outcomes of this visit are two journal papers and one conference paper.

Project title	ISEAWIND – Innovative Structural Engineering Approaches for design of off-shore WIND power plant foundations
Project number	TG4-21
Organisation	Chalmers University of Technology, Architecture and Civil Engineering
Project leader	Rasmus Rempling
Other participants	Alexandre Mathern (Industrial PhD student)
Report for	2014-10-01 – 2018-09-30
Participating companies	NCC AB

Project description

This report is the final report of the project TG4-21. The project has been carried out as a collaboration project between industry and university. The main results include several publications and presentations as well as an examination of a Technical Licentiate.

More than 65% of the power production comes from fossil fuel. At the same time the power consumption will increase with 60% year 2030. This is of course worrying due to the environmental problems associated with burning of fossil fuels. There is a will in society to create change by moving to renewable energy sources; where wind plays an important part as it is verified commercially.

However, the construction industry has identified a need for increasing the body of knowledge with regard to the design and planning of off-shore wind turbine structures (tower-foundation-ground).

The aim is to study the dynamic effects of the complex loading situation of off-shore wind-power plant foundations. The situation is relevant due to the growing concern of design aspects in the engineering community and a broad levelling up of the body of knowledge is essential.

This project has resulted in a Technical Licentiate with unique knowledge in the design, planning and response of off-shore wind power plant structures with focus on the interaction tower-foundation-ground; an essential expertise for the Swedish market of renewable energy sources.

ISEAWIND incorporates four studies, which are all connected to a virtual case-study:

A. Study of the engineering aspects of off-shore foundations in Sweden. This will be approached by a literature study and case-study of the design and execution of an off-shore wind-farm (e.g. Bockstigen).
B. Study of the varying load transfer, tower-foundation-ground, for different load and ground situations, as well as uncracked/cracked concrete. With this study we can predict specific details in the structure that need more attention (Study C). This will be approached by an explicit numerical model in which we can vary the load situation and study the load transition of the structure.
C. Study specific details that are prone to fatigue, e.g. anchor-ring (bolts and concrete), reinforcement and tension rods. This will be approached by implicit numerical models of the specific details.
D. Optional study outside program time frame: Study of the potential of doing continuous structural health checks by updating numerical analyses continuously with live-data. This will be approached by using live-data of a case-study and feed the loading/deformation history to the models of study B and C.

	2015		**2016**				**2017**				**2018**			
Studies	**Q3**	**Q4**	**Q1**	**Q2**	**Q3**	**Q4**	**Q1**	**Q2**	**Q3**	**Q4**	**Q1**	**Q2**	**Q3**	**Q4**
A														
B														
C														
D														

Results

During the reporting period, several studies have been performed.

The first study was an investigation of the engineering challenges for offshore foundations in the Baltic sea. The study includes a survey and combination of data collected from official databases (International and European). The collected data, shows many similarities between Nordic sea and the Baltic sea. However, in order to complete the study, data of geotechnical conditions in the Baltic Sea was needed. The aim of the study has not been fully reached due to this lack of data. The core of the work has been performed at Leibniz University where a joint publication on foundations for offshore wind turbines has been finished and submitted to a scientific journal.

Study on design of three dimensional concrete structures by strut-and-tie models is finished and the results have been presented at a conference. An enhanced and generic three-dimensional strut and tie model has been developed in this work for the design of reinforced concrete foundations and validated with experimental results from tests on four-pile caps found in the literature. The model effectively predicts the ultimate capacity. The consistent three-dimensional geometrical definition proposed for the elements of the strut and tie model ensures an accurate verification at the nodal zones. The strength criterion for bottle shaped struts integrated in the model allows to take into account favourable confinement effects. An automatic iterative procedure has also been successfully applied to adjust the position of the members and to refine the dimensions of the nodal zones under the column with respect to the strength of concrete subjected to a triaxial state of stress.

Numerical FE-study of some experiments performed of load transfer mechanisms in collaboration with Leibniz University. During the spring 2017 and 2018, Alexandre Mathern was a visiting researcher at Leibniz University in Hannover, Germany. FE analyses have been performed on the tests conducted at Leibniz. The aim is to improve the connection between concrete and ductile cast-iron connection for a novel hybrid jacket substructure for offshore wind turbines made of high-strength concrete pipes and connections in ductile cast iron. The results of this study are almost ready for submission.

Several other studies are student work performed at the division of structural engineering, the division of construction management and the division of Geotechnics. The focuses of the MSc theses have been on risk management and structural design. The reports are listed in publications.

The optional study of continuous structural health monitoring has been started and will be continued outside the program and the project.

Fulfilment of SWPTC's goals

The following table is review of how ISEAWIND aims to meet research program criteria:

Research program criteria	ISEAWIND
Active industry	NCC is active with an industrial PhD and a technical supervisor
Cooperation with other research groups	In the different studies there are needs for cooperation with Sjöfart och Marin and Construction Management
Researchers are active in international research	The research group has established international collaboration with Liebniz University.
Swedish development and production of components	Core purpose of ISEAWIND
Excellent research with the purpose to find optimal wind turbines and its components.	The research team is part of the best research group on numerical modelling of reinforced concrete and has a numerous PhD theses on the subject. The experience of this group will be very valuable for the numerical studies.
A well-established research to determine the remaining life of the wind power plant.	

Deviations from project plan

There are some deviations from project plan. Study A took a slight turn due to the lack of data. Instead a joint publication with an international University has been submitted for publication. It was found to difficult to treat study B and C separately. Therefore, it was decided to start study C earlier than planned.

Publications

Conference papers

A. Mathern, R. Rempling, *Innovative Structural Engineering Approaches for the design of offshore WIND turbine support structures*, Offshore Wind R&D Conference 2015, Research at Alpha Ventus, 13-15 Oct., Bremerhaven, Germany, 2015

A. Mathern, R. Rempling *ISEAWIND - Innovative Structural Engineering Approaches for the design of offshore WIND turbine foundations*, Vindkraftsforskning i fokus konferens 2015, 6-7 October, Uppsala, 2015

A. Mathern, G. Chantelot, P-O. Svahn et al., *Enhanced strut-and-tie model for reinforced concrete pile caps*, 39th IABSE Symposium. Vancouver, Canada: IABSE, 2017, pp. 607–614

C. Koch, J. Baluku, I. Habakurama, A. Mathern, *The challenges of building inner sea offshore wind farms - the cases of Lillgrund and Anholt*, 9th Nordic Conference on Construction Economics and Organization, June 13-14, 2017, Göteborg, Sweden

Master theses

Ö. Faruk, H. Mutungi, *Assessment of simulation codes for offshore wind turbine foundations,* Master's Thesis in the Master's Programme Structural Engineering and Building Technology, 2016

I. Habakurama, J. Baluku, *The challenges in installation of offshore wind farms, A case of Lillgrund and Anholt wind farms*. Göteborg: Chalmers University of Technology (Examensarbete - Institutionen för bygg- och miljöteknik, Chalmers tekniska högskola, nr: BOMX02-16-104), 2016

M. Ahlström, C. Holmqvist, *Assessment and comparative study of design method for onshore wind power plant foundations,* Master's Thesis in the Master's Programme Structural Engineering and Building Technology, 2017

E. Ahlgren, E. Grudic, *Risk Management in Offshore Wind Farm Development*. Göteborg, Chalmers University of Technology (Examensarbete - Institutionen för bygg- och miljöteknik, Chalmers tekniska högskola, no: BOMX02-17-61), 2017

J. Isaksson, D. Tenenbaum, *The effect of soil-structure interaction on the behaviour of onshore wind turbines with a gravity-based foundation*, Master's Thesis in Structural Engineering and Building Technology / Master's thesis in Sound and Vibration, 2018

E. Jonsson, E. Tunander, *Alternative evaluation methods for on-shore wind turbines*, Master's Thesis in Infrastructure and Environmental Engineering, 2018

E. Wiklund, *Comparison of structural analysis methods for reinforced concrete deep beams*, Master's Thesis in Structural Engineering and Building Technology, 2018

Submitted papers

A. Mathern, C. von der Haar, S. Marx, *Concrete structures for offshore wind turbines: current status, challenges, and future trends,* submitted to Renewable & Sustainable Energy Reviews

External activities

- Participated and presented at the conference Maritima Klustret – Västra Götaland, 4 Nov 2015, in Gothenburg.
- Presentation at NCC Doktorandträff, 24-25 Nov. 2015, in Gothenburg.
- Participated and presented at the conference RAVE Offshore Wind R&D, 13-15 Oct. 2015, in Bremerhaven, Germany
- Participated and presented at Structural Engineering seminar, 27 Oct 2015, in Gothenburg.

- Participated and presented at the conference Vindkraftsforskning i focus, 6-7 Oct. 2015, in Uppsala.
- Participated to 19th Congress of IABSE, 21-23 Sept. 2016, in Stockholm.
- Presentation at Structural Engineering Day at Chalmers, 24 October 2017
- Attending and presenting at 39th IABSE Symposium, 19-23 Sept. 2017, in Vancouver
- Presentation at NCC PhD seminar, 30 August 2017
- Participated to OFFSHORE WIND ENERGY 6-7 June 2017, London
- Presentation of project and plans with research visit for research group Massivbau at Leibniz Universität, March 2017
- Presentation on Set-Based design at CIR-dagen, January 2017
- Research visits at Institute of Concrete Construction at Leibniz University Hannover, January 2018 and June 2018 (2 weeks) to participate in HyConCast experiments.

Project title	Offshore floating wind power: A study of the Hexicon concept
Project number	TG4-22
Organisation	Chalmers University of Technology, Fluid Dynamics Division
Project leader	Professor Lars Davidson
Other participants	Hamidreza Abedi (Postdoc)
Report for	2016-01-10 - 2017-09-30
Participating companies	Hexicon

Project description

The aim of the project is to determine the maximum expected misalignment between turbine nacelle and platform to avoid blade-wake interaction as a source of destructive oscillatory motions of the wind turbine structure. The focus of the project is to assess the performance that can be expected from setting up active damping on the Hexicon floating structure for more efficient yaw system.

A time-marching vortex lattice free wake (VLFW) based on the incompressible, inviscid and irrotational flow has been developed to study the wake interaction of two adjacent turbines mounted on the same platform (Hexicon's platform concept). A new module has been added to take the turbine's wake expansion into account due to the blade pitch regulation (under the assumption of sheared and steady state upstream flow) in cooperation with the new active control system, currently being developed by TG4-22.

Results

The results display that the induced velocity field due to the presence of turbines in vicinity of each other has a small effect on the wake expansion. However, it slightly affects the generated power and thrust. Moreover, for some specified operating conditions, there is no blade-wake interaction because of the platform and turbines misalignment.

Among different operating parameters such as the upstream flow speed, rotational velocity of rotor and blade pitch angle, the effect of upstream flow speed on wake expansion is larger than the others. Furthermore, wake expansion due to change of operating conditions occurs far from the rotor plane. Hence, it may be possible to decrease the sides of the triangular platform. Different rotor/platform configurations (misalignment between turbine nacelle and platform) corresponding to the implemented control algorithm will be studied later.

Fulfilment of SWPTC's goals

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

- Making offshore wind energy more economically
- Increased lifetime of wind turbines
- Reduced maintenance costs

Deviations from project plan

All the activities (simulation method, results etc.) done during the project were agreed with industrial partner (Hexicon AB) of the project. However, they were not matched with the WPs in the approved project plan.

Publications

Conference papers

H. Abedi, *Influence of generated wind field on Wind-turbine power production in forest Region*, Wind Energy Science Conference 2017, 26-29 June 2017, Copenhagen, Denmark

External activities

Attendance, The Science of Making Torque from Wind (TORQUE 2016), 5-7 October 2016, Munich, Germany.

Project title	Analysis Methodology for Fatigue of Wind Turbine
Project number	TG4-23
Organisation	RISE
Project leader	Anders Wickström, RISE
Other participants	Claes Eskilsson; RISE Fredrik Stig, Swerea Hamid Abedi, Chalmers Martin Rosander, Seatwirl Jonas Boström, Seatwirl
Report for	2018-05-01 – 2018-09-30
Participating companies	SeaTwirl AB

Project description

The main aim of the project is to develop knowledge and deeper understanding of the dynamics and fatigue loads of a vertical axis wind turbine and its interaction with the support structure. Especial the cyclic loads and the potential coupling to the structural dynamic response will be analysed and evaluated. Ultimately the project shall present a design methodology for fatigue assessment of vertical axis wind turbine, with focus on the turbine and its composite material and structure.

A high resolution model will be created by use of a generic method. The Vortex Theory is selected, which is based on the incompressible, inviscid and irrotational flow. It can be used to predict the aerodynamic performance of wind turbines. The advantage of vortex flow is to reduce the flow complexity, and it has been widely used for aerodynamic analysis of airfoils and aircrafts.

Another work package will investigate the cyclic loads acting on the VAWT. A rapid generic simulation model will be proposed, accounting for impact of the cyclic blade loads, centrifugal forces and gravity. The result will be a design methodology for fatigue assessment of vertical axis wind turbines.

The cyclic fatigue loading might be significantly amplified caused by the structural dynamic situation. To evaluate the structural dynamics, the resonance frequencies of the whole floating HAWT will be calculated by FE methods.

The turbine will to a large extent be built of composite materials. Carbon fibre and glass fibre will be used in some combinations. Steel structures will also be used, and special high strength steel will be evaluated if applicable. For all materials, general design criteria need to be evaluated with focus on fatigue properties and strength, also in line with applicable standards

The rigid-body motion of the S2 floating offshore wind turbine due to the wave conditions will be analysed the check for potential resonance with actual wave frequency spectra.

Results

The project has developed knowledge and deeper understanding of the dynamics and fatigue loads of a vertical axis wind turbine and its interaction with the support structure.

The turbine has been modelled in a free wake vortex based code, CACTUS. The results have been compared to CFD high resolution simulations. Although the vortex method predicts higher power (around 16%) and aerodynamic loads compared to CFD, it only requires 0.75 CPU core-hour compared to 28800 CPU core-hour used by CFD. By this method, wind speeds in the operational range have been simulated.

It has been concluded that the blade loads over the azimuth angle are cyclic and can be characterized and represented by Fourier series of order 8 for each selected wind speed, 4, 5, … 25 m/s.

Based on this matrix of wind speeds and Fourier series parameters for the respective load components, a rapid generic simulation model has been created, summarizing the blade loads in a turbulent wind field, blade element by blade element. The impact of centrifugal forces, gravity and rotating bending caused by arbitrary platform inclination are accounted for. The result is a design methodology for fatigue assessment of vertical axis wind turbines. The Fourier series methodology is applicable and relevant for any rotating machinery or turbine.

The methodology has been executed and tested at two spots on the turbine, the strut base and tower base. From the initial structural properties, the fatigue life and integrity has been checked according to wind turbine class 2B and 20 years life.

A finite element model of a vertical-axis wind turbine has created and used to determine the structural eigenfrequencies. The FE-model physical properties are in close resemblance to the “S2” turbine.

A conclusion from the eigenmode analyses is that there is a premium on keeping weights down. Low weight can translate into lower stiffness requirements of the tower. As the tower is made from steel, the weight penalty on increasing tower stiffness is relatively high. High tower weight also results in a larger displacement floating structure. As the entire under-water body is rotating in the SeaTwirl concept, a larger under-water body not only becomes more expensive, it also results in larger frictional losses from viscous water friction.

Part of the project and results is a literature survey and interviewing a blade designer. The result is 13 relevant references. These scientific papers are general with respect to horizontal/vertical axis wind turbines with respect to the material. However, there are differences in the structural response, which is addressed in some papers.

The rigid-body motion of the S2 device due to environmental loads (wind, current and waves) was modelled with a linear radiation/diffraction model including mooring dynamics. The model can be used to estimate fatigue loads due to wave induced acceleration. The device has a resonance peak at 19 s in heave, but the S2 device is starting to see significant response after 16 s. The mooring coupling causes the pitch response to increase after 16 s with a peak around 20 s.

In all, the project has been successful and exceeding expectations in terms of provided results, software, mooring dynamics, references, strength results and general knowledge.

Fulfilment of SWPTC’s goals

In a tangible way the project has addressed the common goal of the SWTPC to build system knowledge to enable development and production of complete wind turbines in Sweden with specific and concrete support for Swedish industry. Results are also applicable to other machineries and wind turbine components.

Deviations from project plan

No deviations from project plan reported.

Publications

No publications but a final report of the entire project and its results is created:
TG4-23-1 Report out, Analysis Methodology for Fatigue of Wind Turbine, SeaTwirl

External activities

No external activities.

Project title	Load and risk based maintenance management of wind turbines
Project number	TG 5-1
Organisation	Chalmers University of Technology, Electric Power Engineering
Project leader	Ola Carlson
Other participants	Pramod Bangalore (PhD student)
Report for	2014-10-01 – 2016-09-30
Participating companies	Göteborg Energi, Stena Renewables, Gold Wind, Greenbyte

Project description

The main aim of this project was to increase the availability of wind turbines while reducing the overall costs of maintenance.

Below is a short summary of the project:

A. An artificial neural network (ANN) model was proposed which utilizes data stored in the SCADA system for early detection of faults in critical components of the wind turbine.

B. An automated procedure to decide and update the training data set was proposed; the proposed procedure enables the selection of individual training data sets for each wind turbine.

C. Data filtering methods were presented to clean the often noisy SCADA data in order to create robust ANN models.

D. A statistical outlier detection approach was proposed to analyze the signals from the ANN model, and to decide the threshold for anomalous operation.

E. Case studies were performed to validate the ANN-based condition monitoring methodology with data from real wind turbines.

F. A maintenance management framework–the Self-Evolving Maintenance Scheduler–was proposed. The SEMS frameworks provides guidelines for utilization of data from different sources for maintenance optimization.

G. A mathematical model for maintenance optimization referred to as Preventive Maintenance Problem with Interval Costs (PMSPIC) was utilized to create optimal maintenance schedules considering age based failure rate models.

H. Modifications in the original PMSPIC model were proposed to enable condition based preventive maintenance scheduling utilizing the condition based failure rate models.

I. A case study was performed to show the application of the condition based preventive maintenance optimization routine applied along with the ANN based condition monitoring method within the proposed maintenance management framework.

Results

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 and generator are critical components in the wind turbine, which accounts for a considerable portion of the total downtime.

An ANN based condition monitoring methodology was created, which utilizes the measurements stored in SCADA for an early detection of faults in the components being monitored. Figure 14 presents the output from the ANN-based condition monitoring system for a wind turbine, which had recorded a failure in the gearbox bearing. The system was able to detect the fault in the gearbox bearing in advance, providing an opportunity to plan the replacement activity.

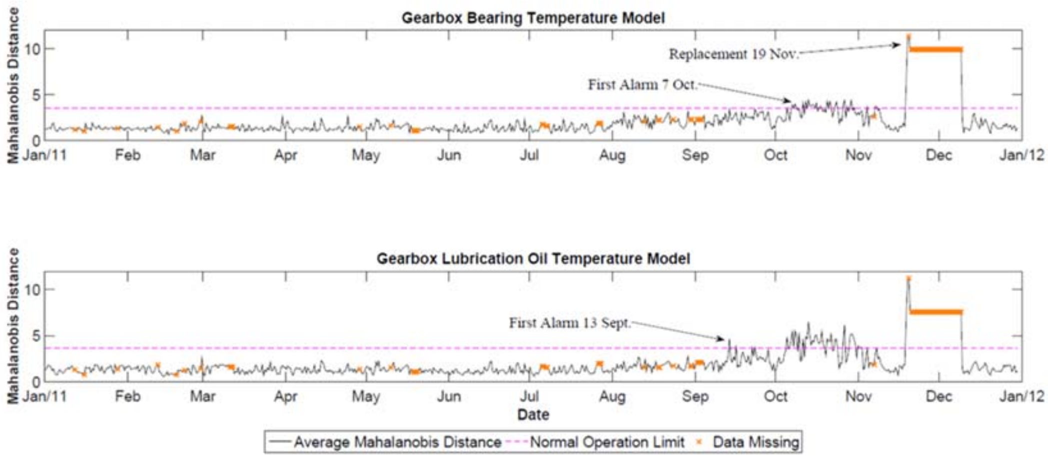


Figure 14 Output from the ANN-based condition monitoring system for a wind turbine with gearbox bearing fault

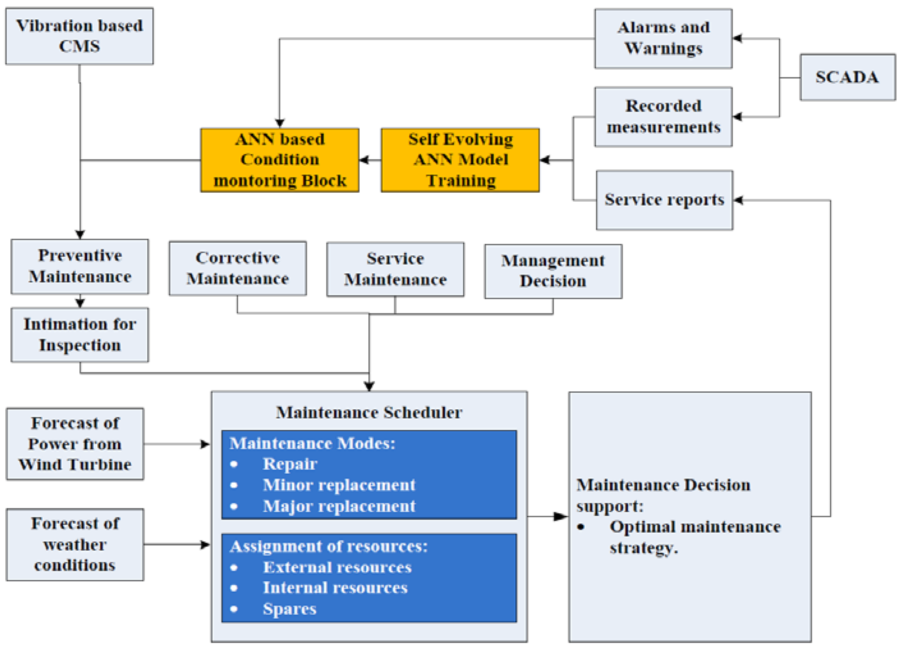


Figure 15 SEMS maintenance management framework

A maintenance management framework, referred to as SEMS (Self-Evolving Maintenance Scheduler), was proposed, and is presented in Figure 15. The SEMS framework incorporates the indication of failure from various CMS systems in order to plan maintenance activities. The SEMS framework also considers opportunities to perform maintenance on other components in order to optimize the total maintenance cost over the entire life of the wind turbine.

The preventive maintenance scheduling problem with interval costs (PMSPIC) mathematical model was utilized to provide the initial optimized preventive maintenance schedule with age-based failure rate models. Modifications in the PMSPIC model were suggested to enable condition-based maintenance scheduling in real time and considering the signals from condition monitoring systems. Figure 16 presents the output from the PMSPIC based scheduler for a case study, where the indication of deterioration in the gearbox was obtained in month 20.

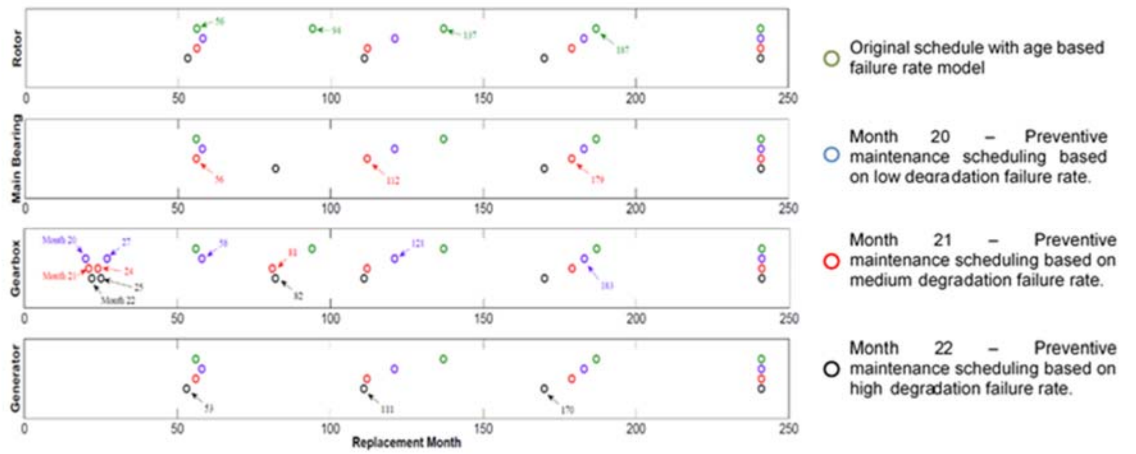


Figure 16 A typical output of an optimized maintenance schedule based on condition-based failure rate model for a test wind turbine

Fulfilment of SWPTC's goals

This project contributes towards SWPTC's goal of increasing the availability of wind turbines while reducing the maintenance costs. The aim is to develop a maintenance strategy based on measured information about the conditions of the components, and the costs associated with performing maintenance. Such a strategy will aid in effective maintenance, lower downtimes and lowering total costs.

Deviations from project plan

No deviations from the project plan.

Publications

Doctoral thesis

P. Bangalore, *Load and risk based maintenance management of wind turbines*, Doctoral Thesis, Dept. of Energy and Environment, Chalmers University of Technology, Gothenburg, Sweden, 2016

Journal papers

P. Bangalore and L. B. Tjernberg, *An Artificial Neural Network Approach for Early Fault detection of Gearbox Bearings*, IEEE Transactions on Smart Grid, vol.6, no.2, March 2015, pp.980-987

P. Bangalore, S. Letzgus, D. Karlsson, and M. Patriksson, *An artificial neural network based condition monitoring method for wind turbines, with application to the monitoring of the gearbox*, Wind Energy. Vol. 20 (8), p. 1421-1438, 2017

P. Bangalore, and M. Patriksson, *Analysis of SCADA data for early fault detection, with application to the maintenance management of wind turbines*, Renewable Energy. Vol. 115, p. 521-532, 2018

Conference papers

P. Bangalore, S. Letzgus, and M. Patriksson, *Analysis of SCADA data for early fault detection with application to the maintenance management of wind turbines*, presented at Cigre Session 46, Paris, August 2016

Master theses

S. Letzgus, *SCADA-Data Analysis for Condition Monitoring of Wind Turbine Components*, Master Thesis, Dept of Energy and Environment, Chalmers University of Technology, Gothenburg Sweden, 2015

D. Karlsson, *Wind Turbine Performance Monitoring using Artificial Neural Networks*, Master Thesis, Dept of Energy and Environment, Chalmers University of Technology, Gothenburg Sweden, 2015

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.
- Visit to Gold Wind facility in Beijing.
- Master thesis with Stena Renewables
- Master thesis with Green Xtreme

Project title	Characterizing and modelling of bearing current activity
Project number	TG5-2
Organisation	Chalmers University of Technology, High Voltage Engineering
Project leader	Jörgen Blennow
Other participants	Abhishek Joshi (PhD student)
Report for	2014-10-01 – 2016-12-31
Participating companies	

Project description

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 objective with this project is to increase the knowledge of the mechanisms behind current induced damages in wind power applications based on modelling and experimental work. The focus will be on understanding of the discharge mechanism present and of how the damages occur.

Results

The main achievements in the project during the period are shortly summarised below.

Investigations in memory effects in recovery of insulating properties of bearing

Electrical breakdown of the lubricant film in a running bearing at dimensionless speeds of 30000 (2000 rpm) and an axial load of 4 N is found to occur at DC electric field strength of 29.6 V/µm, upon step-wise increment of electric field strength across the bearing in steps of 3.7 V/µm. After the bearing is exposed to high electric field stress, the bearing current activity causes the bearing to lose its insulating ability. This is referred to as 'memory effect' and is corresponds to inability of electrical insulation of bearing to withstand electrical stress after being exposed to high electric field stress, as shown in Figure 17. The memory effect is seen to affect the insulating ability of the bearing, and could last for as long as 2 hours after exposure to bearing current activity, and given that no grounding is provided to the bearing. Minor current conduction in the bearing is found to initiate at electric field stress of 14 and 20 V/µm, while the extinction electric field level for current conduction is found to be between 8.4 and 5.6 V/µm.

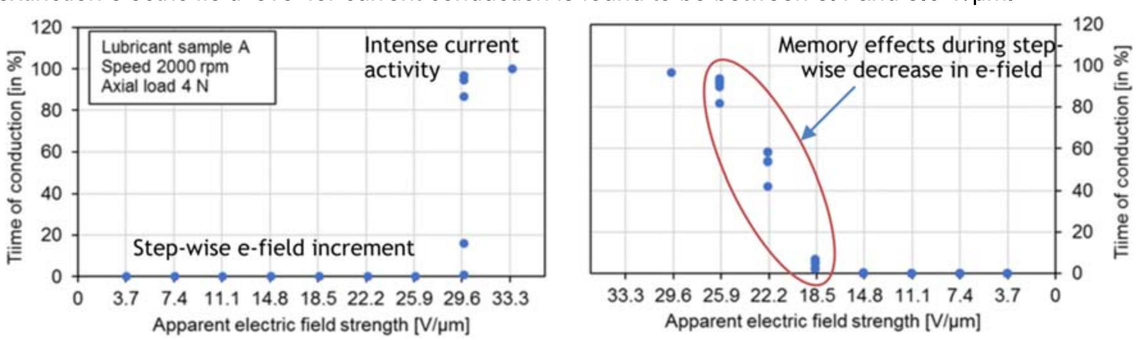
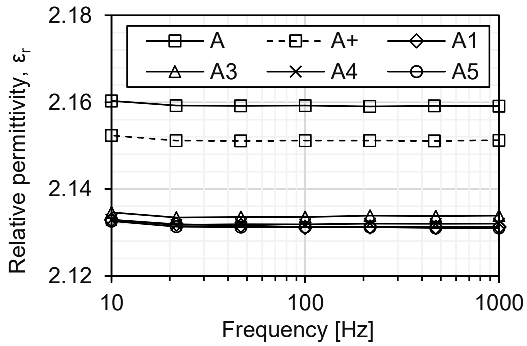


Figure 17 Breakdown of electrical insulation of bearing occurs at e-field of 29.6 V/µm, seen when e- field is step-wise increased. Upon decreasing the e-field after intense current activity, the bearing shows memory effects, where it fails to recover electrical insulating ability at lower values of e-fields.

Frequency domain spectroscopy of lubricants

Relative permittivity (ε_r) and dielectric loss factor (tanδ) of different lubricant samples was measured at 50 °C using frequency domain spectroscopy as a function of swept frequency. The particle concentration was kept fixed at 150 mg/L. The relative permittivity of the samples with particles (i.e., A1 – Arizona test dust, A3 – Aluminium powder, A4 – Fine iron powder) and electrically aged sampled (A5) is slightly lower (ε_r = 2.13) than the virgin Sample A of (ε_r = 2.16), as shown in Figure 18. Dielectric loss factor (tanδ) only slightly increase after running-in process (A+), but by addition of particle and electrically aging the lubricant by arcing results in slight decrease in tanδ. A very minor change in these properties suggest that inclusion of foreign particles and processes such as running-in and electrically aging of the samples do not result in significant change in dielectric properties of the lubricant.



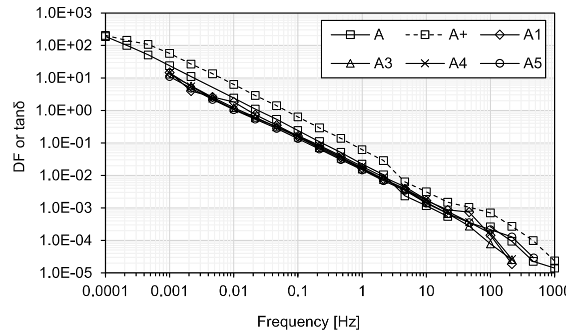


Figure 18 Relative permittivity (left) and dielectric loss factor, tanδ (right) of lubricant samples shown at 50 °C. Adding particles to the samples and electrically aging samples does not alter the relative permittivity and DC conductivity of the samples. The dielectric loss factor in Samples A1, A3, A4 and A5 is only slightly lower than that of Sample A.

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 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 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. The project 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

Finalising the doctoral thesis and submission of two journal publications which are in process of being completed have been delayed. A technical report has been submitted to the project partners, and is recorded in CPL. Tests have been made to quantify asperity contacts, and the submission of the journal paper is delayed. The journal paper will be submitted during spring 2019. The doctoral defence is aimed to be held in March 2019.

Publications

A. Joshi, *Electrical Characterisations of Bearings*, Doctoral Thesis, Dept. of Electrical Engineering, Chalmers University of Technology, Gothenburg, Sweden, 2019, submitted to opponent and committee

External activities

The project was presented at a wind conference, *Vindkraftsforskning i fokus*, 6-7 October, 2015 in Uppsala, Sweden

Project title	Optimal maintenance of wind power plants
Project number	TG5-21
Organisation	Chalmers University of Technology, High Voltage Engineering
Project leader	Michael Patriksson
Other participants	Quanjiang Yu (PhD student)
Report for	2014-10-01 – 2018-09-30
Participating companies	Greenbyte, Göteborg Energi, NCC Sverige, Rabbalshede Kraft, Röbergsfjället Vind, Stena Renewable

Project description

Climate change now affects every country on every continent. It disrupts national and personal economies, affects lives, communities and countries, today and even more tomorrow. To address climate change 195 countries have signed the Paris Agreement, agreeing to work towards limiting global temperature rise to well below 2 degrees centigrade, and given the grave risks, to strive for a minimal raise from 1.5 degrees centigrade. Climate change mitigation generally involves dramatic reductions in human-induced emissions of greenhouse gases. Wind power as a clean energy is available in abundance, it's renewable, and it produces almost no greenhouse gas emissions during operation. The area of wind turbine operations & maintenance represents a growing segment and business opportunity in the wind energy industry.

The goal for Quanjiang Yu in the project Optimal maintenance of wind power plants (July 2016–) is to develop an app, which uses maintenance data (corrective maintenance (CM) costs, preventive maintenance (PM) costs, survival functions, logistic costs, etc.) as input, and generates a short-term maintenance schedule which will indicate to the maintenance staff, who are on site, those components which have the highest probabilities of failing within a short time span. The app should also connect to the SCADA system, so it can change inputs like survival functions based on the data gathered from the SCADA system.

We also develop a program which can generate a long-term maintenance schedule. It allows wind turbine owners to have a long-term plan, to give them some leverage on bargaining how much they should pay for a 5-years maintenance contract, estimate how many spare parts they should purchase, and so on.

Results

For the short-time maintenance schedule, a new optimization model – called STPMP (short-term preventive maintenance problem) – has been built.

The basic idea is: for a wind farm contain a certain number of wind turbines, we want to minimize the maintenance cost. For different components, they have different survival function which indict how often that component break down. Based on the survival function and the costs to perform maintenance, we calculate the average corrective maintenance cost and preventative maintenance cost and pick the lowest one.

Figure 19 below shows a case study for a gear box. From the left figure, we can see that at the beginning, the cost of choosing to perform PM is really high, due to the low risk of the component failing. After a while, the cost of performing PM becomes lower than performing CM, and if we consider the time steps 20–80, represented in the right figure, we can see that around month 53 we get the best solution, which following the PM maintenance schedule yields a cost which is around half the cost of the CM schedule; it is a huge difference.

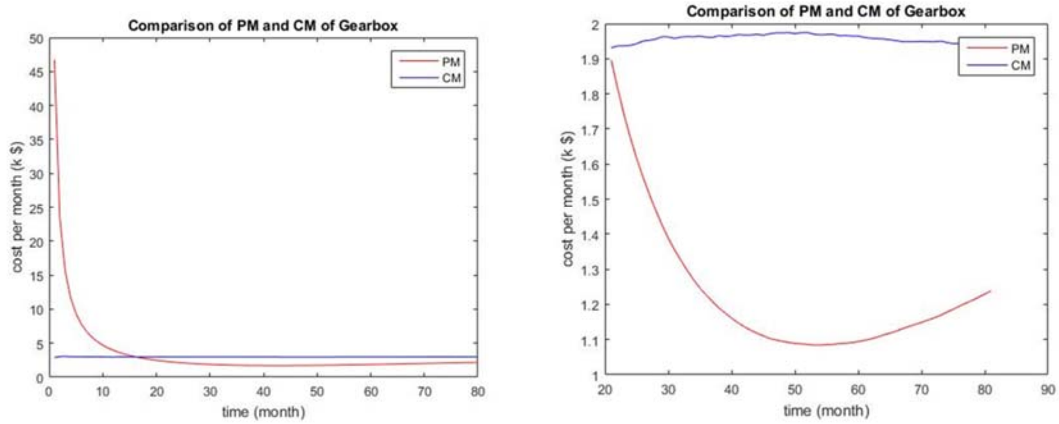


Figure 19 A case study for a gear box

After building the new optimization model STPMP, we performed a comparison between STPMP and PMSPIC. The solution time is composed by two parts: first the calculation of the parameters of the models, and then the time to actually solve them. From Table 1 we can see the time to solve the models; STPMP is much faster than PMSPIC, especially for small time steps. The results also show that STPMP provides equally good results as PMSPIC:

	Two optimization models	Solution time (Matlab + CPLEX)		Results
		Calculate the parameters with Matlab	Solve the model with CPLEX	
Time step length **1 month**	STPMP	49.19 sec	0.018 sec	5.06(k $) per month
	PMSPIC	51.12 sec	113.08 sec	5.01(k $) per month
Time step length **3 days**	STPMP	442 sec	0.094 sec	0.506(k $) per 3 days
	PMSPIC	514 sec	Over 5 hours	

Table 1 A comparison between STPMP and PMSPIC

From this model, based on different weights on cost and risk, we can generate a series of maintenance models, by playing with the CM cost. If the wind turbine owners want the reliability to be really high, we can make the CM cost higher. If the wind turbine owners want the components work as long as possible, we can make the CM cost lower.

To make the model more accurate, we connect the model with the condition monitoring system or SCADA system. We developed a method which incorporates elements from stochastic modeling with time-dependent covariates to represent the uncertainty of component lives; those covariates are calculated from the condition monitoring systems or SCADA system. We can combine the short-term model with the data we receive from the condition monitoring system or SCADA system. To do so, the first step is to incorporate historical alarms. We developed a model describing how the parameters of the Weibull distribution depend on the covariates (i.e, alarms). We choose log-linear models for both parameters, i.e., models of the form $\log k = a + bx$, where b and x are vectors and k is one of the parameters of the Weibull distribution; we choose x as the number of alarms (up to time t). Maximum likelihood is used to estimate the parameters a and b, which in turn determine the parameters of the Weibull distribution. The alarms enter according to a point process in time, which are time-updated covariates. In the end, we can make predictions on the remaining life of components. To do so, we can use the stored information about the past and update the distribution as new alarms enter. So, every time a new alarm enters, the Weibull distribution will be changed.

This method can also be used to look at other kinds of data, like the gearbox bearing temperature and gearbox oil temperature. By analyzing this data, we can have a better estimate on the survival function, and hence generate a better maintenance schedule.

Solving STPMP is really fast, so it can be used to generate a short-term schedule, and even be implemented in an app. For long-term scheduling, or if the wind turbine owner wants to look at the whole picture, we can use PMSPIC. Its complexity implies the need for longer time steps and a numerical termination criterion, based on lower and upper bounds on the optimal objective function value.

During this period, we also supervised a candidate project: Experiments on optimal maintenance operations with emphasis on end-of-contract constraints. This project focused on what will happen if we don't plan to perform maintenance at the end of the contract period, or at the end of the wind turbines' life time. From the results obtained, we can see that the shape of the PM schedule is still the same – we just move it to some earlier time steps.

Fulfilment of SWPTC's goals

This project contributes to the fulfilment of several of the Centre's goals, in particular to the profitability of wind power. It tries to increase the reliability of wind turbines and decrease the cost of maintenance. The aim is to develop a tool, which can indicate to the maintenance personnel what they should do next, more specifically when and which component they should maintain.

Deviations from project plan

The project is behind the anticipated schedule, regarding the collection and analysis of the condition data from the member companies. This will not affect the end result of the project.

Publications

A manuscript on the short-term preventive maintenance problem will be submitted to *European Journal of Operational Research* (EJOR) this month; EJOR recently announced a call for papers on applied combinatorial optimization.

External activities

- The project was presented at a mathematics conference, SOAK 2017, October 19–20, in Linköping, Sweden.

- Participated and presented in Vind2016, Oct. 2016-10, in Stockholm.
- Participated in a winter school: optimization and operations research, June 2017, in Zinal
- Participated in Seventh GIGAWIND Symposium, March 2017, in Hannover
- Participated in Energy Transition 2017, March 2017, in Trondheim
  Participated and presented in Wind Energy Science Conference, June 2017, at DTU Lyngby

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	2014-10-01 – 2015-01-31.
Participating companies	Vattenfall AB, Skellefteå Kraft, H Gedda Consulting, Bollebygd Plast.

Project description

The project will 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 will contribute with experience and participate in planning of the whole project. H Gedda consulting has long experience from deicing equipment and will assist in the planning and evaluation of the measurements. Bollebygds Plast will contribute with laminates of own design which will be evaluated in cold laboratory at LTU.

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

The project will be initiated by a planning meeting for the wind power measurements. Suitable machines with icing conditions will be evaluated and a plan for the measurement will be made. The target of the first year is to evaluate equipment and techniques for measurements during year two.

In the project, lab-tests were used to develop techniques for modeling and measurements. The analytical modeling consists of heat transfer modeling of heated laminate with ice and degradation of the laminate due to heat. In these tests test plates of 0.5×1m was used with heating introduced by electric connection to one layer of carbon fiber mat. Several sets of test plates was manufactured by SICOMP and Bollebygds Plast and evaluated in climate room at LTU. The target was to develop experimental technique and theoretical models of the deicing process. From the experiments the simulation models was evaluated.

On the test site in Uljabouda measuring techniques was evaluated for measuring the functionality of the heating system. Before each winter it is essential to verify that the heat is uniform on the blade to avoid failure during the winter. Typical problems are hotspots which make the heating impossible to use and therefore severe loss of power is expected during the winter season due to ice. A technique with thermal camera on a mini helicopter was selected and evaluated during the project.

The initial plan was to run the project for two years but due to the delay to introduce phase 2 of the center the project was extended to the end of mars 2015. See Figure 1. During this time the experimental technique in the climate room was further developed.

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

During 2015 the project has been presented at Winterwind 2015, Piteå, 2-4 February, 2015 (Efficiency and influence of heating device on wind turbine blades). New tests was performed with developed test plates and technique for thermal measurements on real wind turbines was developed. At the university some student projects were used to evaluate new techniques for deicing. Below some key progress are listed.

In the project there is an aim to get thermal measurements on a real wind turbine the deicing process. To do the measurements we early selected a mini helicopter with thermal camera. 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 October 2014. During this measurement the temperature distribution was evaluated during the heating process. It was concluded that the method is useful for detecting hotspots but the temperature resolution is not enough for detailed calibration of simulations. The method is also too sensitive to whether conditions why a better method has to be used in future. With higher resolutions on heat cameras it is likely that a method with measurements from the ground can be used in a near future.

Previously manufactured second set of test plates with balsa core was complemented with an extra plate with Lycel. The new plate will be used to compare the performance of using Lycel instead of balsa.

The second set of test plates were first evaluated in room temperature. Due to the balsa core it was essential to calibrate the thermal properties of balsa. It was found that there was a big difference in thermal properties compared to tabulated values. A possible reason is that the vacuum injection method will force resin in to the core material. The plates were then evaluated in the climate room where ice of different thickness was melted during different heat input. See Figure 20. The plates were measured in vertical position and the initial slide of the ice was detected as the time for deicing. This point was also easy to detect from the temperature sensors. These tests were then used for evaluation of the simulation models.

The simulation models has been calibrated (the properties of balsa) against experiments on the new test plates in room temperature. The models were then validated against experiments on the test plates II with ice. In the one dimensional FEM the ice was modeled including the transition from ice to water. In Figure 21 the measurements and simulations are compared. Two cases are shown 300W/m^2 and 500W/m^2 for 10 mm ice on the plate. Following the red temperature at 300W/m^2 the temperature rises the first 15 minutes until the ice starts to melt. Then the temperature stays at about 0 deg for 10 minutes before the ice is sliding from the surface. This is shown on the rise of temperature after 25 minutes. Comparing with different ice thicknesses the measurements show that it takes shorter time of melting when the ice thickness is increased.

Figure 20 Test setup in the climate room.

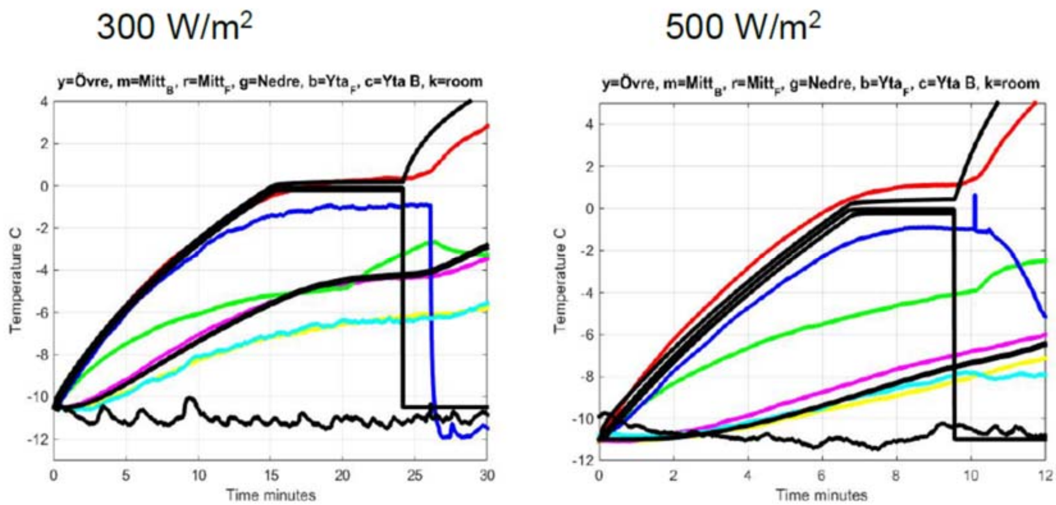


Figure 21 Experiment and Simulation of the deicing process for the test plate. Pink- measurement back side of the core, Red- front side of the core, Red at the interface ice/plate, Black- Simulations for the same positions.

Several student projects have earlier been performed to evaluate different deicing techniques. During this period one project on piezoelectric actuators has been investigated to see if it is a possible method for deicing. The results are promising and we will continue with a master theses project to evaluate the method experimentally.

Paper I from the experiment will be published at a suitable conference. So far some of the results has only been presented at Winterwind 2015.

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

No further deviations during this period.

Publications

J-O. Aidanpää, *Efficiency and influence of heating device on wind turbine blades*, Presentation at Winterwind 2015, Piteå, 2-4 February, 2015

External activities

No external activities were performed during this period.

Project title	Increased reliability of heating systems on wind turbine blades
Project number	TG6-21
Organisation	Swerea SICOMP AB
Project leader	Lars Liljenfeldt
Other participants	Daniel Eklund, Runar Långström, Kurt Olofsson, Rolf Lundström
Report for	2016-01-01 – 2018-09-30
Participating companies	Blade Solutions, Skellefteå Kraft

Project description

The project has mainly been performed by senior personnel at Swerea SICOMP. The industrial partner Skellefteå Kraft has supported with specifications for monitoring system, specifying typical damages, giving requirements for repair methods and accommodating repair on selected damages on wind turbine blades. Blade Solutions has contributed with experience and has participated in the development of repair methods. Blade Solutions has also verified developed methods by conducting repair on site.

The project has been running for over two and a half years. During this period experimental techniques have been developed at Swerea SICOMP as well as on real wind power turbines. The main activities conducted by Swerea SICOMP have involved repair methods, inspection of de-icing systems and damage studies. Reliable methods for blade repair are still a very important issue. It is essential to improve both methods and material used to achieve accurate and fast repair on damaged areas. New types of hotspots and electrical cable breakage are occurring on certain locations. Reasons for that need to be understood and solved, combined with dedicated methods for the different types of damages. One task has involved inspection of de-icing systems to verify the functionality. This inspection must be fast and easy to operate in order to minimize time and cost. Methods and equipment commercially available today have been looked into. Damage studies focused on documented damage reports from the wind park Blaiken. Initially the damage studies were aimed to study the observation that wind turbines located in northern areas seem to be affected by more and severe damages on the blades compared to wind turbines placed in non-arctic conditions. Efforts were made but no relevant data was found, therefore the studies have instead focused on data from Blaiken.

The project was initiated by a start-up meeting with the involved partners, followed by project meetings on a regular basis to report conducted work and to decide on coming activities. In this project, it was vital that activities were in line with the industrial partners' development areas. Even though the main activities still were valid, new focus areas were looked into when appropriate for the project. After completed activities, decision was made by the project group if the activity was to be continued or if the achieved results were sufficient.

An important task was information collection as well as dissemination. Winter Wind, a Swedish conference and exhibition, is one source of interest that has been visited. The project has also been disseminated at other seminars and conferences.

Results

The main focus in the project has been on repair methods. One repair method has been verified on-site and another repair issue has been investigated. In 2016 an activity started how to exchange/repair electrical cables inside a 45 m blade that supports the heating system. Two cables are used for the heating system. When one gets broken, the other cable overloads leading to hotspots/burning and the whole heating system will be out of order.

Inside a blade, it is possible to work approximately 20 m into the blade until it gets to narrow. Then you have >25 m with a very limited space where you must find a possible repair method.

The main activities during the project have been:

2016

- Contacts with companies relining pipes. They are accustomed to working in narrow and long pipes.
- Experiments with different techniques to place a tube inside the prototype blade and evaluating adhesion for different material combinations.

- A box in wood was built to simulate the inside of a narrow and long blade, see Figure 22 below. A prototype equipment was designed and manufactured in order to conduct different experiments.

Figure 22 Wooden box with an imbedded tube where an electrical cable can be placed.

2017

- Development of equipment, see Figure 23, to be able to place and attach a tube with glass fiber reinforcement and resin inside a blade.
- Verification test in laboratory where a tube was attached in a 12 m narrow box. The experiment was successful and documented with video camera.
- On-site verification test was conducted in December 2017 inside a wind turbine blade by Blade Solutions with support of personnel from Swerea SICOMP. The wind turbine is owned by Skellefteå Kraft and is located in the wind park Jokkmokksliden in the vicinity of Malå.
- In this particular case, a 3 m cable was attached directly on the inner surface of the blade. The same carriage as in the earlier verification test at Swerea SICOMP was employed.
- Two studies were conducted and completed:
  - A survey of temperature sensors in windmill blades.
  - Thermography for inspection of active blade de-icing systems.

Figure 23 Development of equipment for attaching a tube in narrow spaces.

2018

- A blade heating system with two overlapping carbon fiber layers in the leading edge has been investigated. Cable breakage with this design can cause major problems for a blade. Test plates were manufactured to simulate the design and the problem. A project meeting involving service personnel at Skellefteå Kraft has been conducted with the purpose to make them aware of the problems and to discuss how to monitor and avoid them.
- Long-term testing to monitor the heating system, see Figure 24, and to find a method to detect cable breakage with RCD-equipment. The long-term testing caused no major damages as Skellefteå Kraft

has experienced but indications exist for failure. The method for detecting cable breakage seams promising and should be developed further.

- Damage studies: Data has been received from Skellefteå Kraft but the analyses gave no clear conclusion when and why the damage occurred and how to prevent the observed damages.

Figure 24 Outside long-term testing of test panels.

Fulfilment of SWPTC's goals

Cold climate issues are central for SWPTC as well as for wind turbine operators such as Skellefteå Kraft and for repair and maintenance companies as Blade Solutions. The overall goal with the research project was to secure the operation of wind turbines in icing conditions and facilitate the development of new wind farms. The project was well in line with SWPTC's intensions.

Deviations from project plan

No major deviations during the project. Some activities have been adjusted to adapt to industrial needs.

Publications

A ¨Good example¨ has been published by Swerea from the work with the repair method.

Four reports have been written and reported:

- Swerea SICOMP CR17-009 Temperature Sensors in Windmill Blades
- Swerea SICOMP CR17-010 Thermography for Inspection of Active Blade De-icing Systems
- Swerea SICOMP CR18-005 Methods for replace of electrical cables inside a wind turbine blade
- Swerea SICOMP CR18-013 Investigation and long-term testing of blade heating system with dual carbon fiber layers

External activities

The project has been presented at:

- Wind power conference at Chalmers, Gothenburg 2017-04-03
- A seminar in Varberg 2018-04-24 within Swedish Composite Association.

Publications

Doctoral theses

J. Härsjö, *Modeling and analysis of PMSM with turn-to-turn fault*, Ph.D. thesis, Chalmers University of Technology, 2016

N. Espinoza, *Wind Turbine Characterization by Voltage Source Converter Based Test Equipment*, PhD-Thesis, Chalmers University of Technology, December, 2016

H. Abedi, *Development of Vortex Filament Method for Wind Power Aerodynamics*, PhD thesis in Thermo and Fluid Dynamics, Department of Applied Mechanics, Chalmers University of Technology, Göteborg, 2016

B. Nebenführ, *Turbulence-resolving simulations for engineering applications*, Doctoral thesis, Chalmers University of Technology, September 2015

S. Asadi, *Wind turbine drive train system dynamics: Multibody dynamic modeling and Global Sensitivity Analysis*, PhD Thesis, Chalmers University of Technology, 2018

M. K. Vakilzadeh, *Stochastic model updating and model selection with application to structural dynamics*, Doctoral thesis, Göteborg: Chalmers University of Technology, 2016

P. Bangalore, *Load and risk based maintenance management of wind turbines*, Doctoral Thesis, Dept. of Energy and Environment, Chalmers University of Technology, Gothenburg, Sweden, 2016

A. Joshi, *Electrical Characterisations of Bearings*, Doctoral Thesis, Dept. of Electrical Engineering, Chalmers University of Technology, Gothenburg, Sweden, 2019, submitted to opponent and committee

Licentiate thesis

S. Asadi, *Drive Train System Dynamics Analysis*: *Application to Wind Turbines,* Thesis for the degree of Licentiate of Engineering, 2016:01, ISSN 1652-8565, Department of Applied Mechanics, Chalmers University of Technology, Göteborg, Sweden

Journal papers

N. Espinoza, M. Bongiorno, O. Carlson, *Novel LVRT Testing Method for Wind Turbines Using Flexible VSC Technology*, in Sustainable Energy, IEEE Transactions in vol.6, no.3, pp.1140-1149, July 2015

M. Beza, M. Bongiorno, G. Stamatiou, L. Harnefors, *Analytical Derivation of the AC-Side Input Admittance of a Modular Multilevel Converter With Open- and Closed-Loop Control Strategies*, IEEE trans. Power Del., May 2017

H. Abedi, L. Davidson, S. Voutsinas, *Enhancement of free vortex filament method for aerodynamic loads on rotor blades, Journal of Solar Energy Engineering*, Transactions of the ASME, Vol. 139 Nummer/häfte 3 s. Article number 031007, 2017

B. Nebenführ and L. Davidson, *Large-Eddy Simulation Study of Thermally Stratified Canopy Flow*, Boundary-Layer Meteorology, August 2015, Volume 156, Issue 2, pp 253-276

B. Nebenführ and L. Davidson, *Prediction of wind-turbine fatigue loads in forest regions based on turbulent LES inflow fields*, Wind Energy. Vol. 20 (6), p. 1003-1015, 2017

S. Struggl, V. Berbyuk, H. Johansson, *Review on wind turbines with focus on drive train system dynamics*, Wind Energy, Vol. 18, 4, p. 567-590, 2015 http://dx.doi.org/10.1002/we.1721

S. Asadi, H. Johansson, *Multibody dynamic modelling of a direct wind turbine drive train*, Wind Energy Science Conference 2017, 26-29 June 2017, Copenhagen, Denmark

S. Rahrovani, M. K. Vakilzadeh, T. Abrahamsson, *Modal Dominancy Analysis Based on Modal Contribution to Frequency Response Function H2-norm*, Mechanical Systems and Signal Processing, 48(1-2), pp. 218-231, 2014

M. K. Vakilzadeh, Y. Huang, J. L. Beck, T. Abrahamsson, *Approximate Bayesian Computation by Subset Simulation Using Hierarchical State-Space Models*, Mechanical Systems and Signal Processing, Available online 4 March 2016, ISSN 0888-3270, http://dx.doi.org/10.1016/j.ymssp.2016.02.024
M. K. Vakilzadeh, V. Yaghoubi, A.T. Johansson, Thomas J.S. Abrahamsson, *Stochastic Finite Element Model Calibration Based on Frequency Responses and Bootstrap Sampling*, Mechanical Systems and Signal Processing. Vol. 88, p. 180-198, 2017

M. K. Vakilzadeh, J.L. Beck, T. Abrahamsson, *Using Approximate Bayesian Computation by Subset Simulation for Efficient Posterior Assessment of Dynamic State-Space Model Classes*, IAM Journal of Scientific Computing. Vol. 40 (1), p. B168-B195, 2018

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P. Bangalore and L. B. Tjernberg, *An Artificial Neural Network Approach for Early Fault detection of Gearbox Bearings*, IEEE Transactions on Smart Grid, vol.6, no.2, March 2015, pp.980-987

P. Bangalore, S. Letzgus, D. Karlsson, and M. Patriksson, *An artificial neural network based condition monitoring method for wind turbines*, with application to the monitoring of the gearbox, Wind Energy. Vol. 20 (8), p. 1421-1438, 2017

P. Bangalore, and M. Patriksson, *Analysis of SCADA data for early fault detection, with application to the maintenance management of wind turbines*, Renewable Energy. Vol. 115, p. 521-532, 2018

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J. Härsjö, M. Bongiorno, *Modeling and harmonic analysis of a permanent magnet synchronous machine with turn-to-turn fault*, 2015 17th European Conference on Power Electronics and Applications (EPE'15 ECCE-Europe), 8-10 Sept. 2015, Geneva, Switzerland

N. Espinoza, M. Bongiorno and O. Carlson, *Frequency Characterization of Type-IV Wind Turbine Systems*, in 2016 IEEE Energy Conversion Congress and Exposition (ECCE), Milwaukee, WI, 2016O. Carlson,

N. Espinoza, *Grid code testing by Voltage Source Converter,* Wind Energy Science Conference 2017, Technical University of Denmark, Lyngby Campus, 26 - 29 June 2017

M. Beza, M. Bongiorno, *Stability of grid-connected modular multilevel converter with open- and closed-loop ac-side control*, European Conference on Power Electronics and Applications, Sept. 2017

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, 14-20 November 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.

H. Abedi, L. Davidson, S. Voutsinas, *Development of free vortex wake model for wind turbine wake aerodynamics under yaw condition*, 34th Wind Energy Symposium, 4-8 January 2016 San Diego, USA.

S. Asadi, V. Berbyuk, H. Johansson, *Vibration dynamics of a wind turbine drive train high speed subsystem: Modeling and validation*, Proceedings of the ASME 2015 International Design Engineering Technical Conferences and Computers & Information in Engineering Conference IDETC/CIE, August 2-5, 2015, Boston, Massachusetts, USA, paper DETC2015-46016, http://dx.doi.org/10.1115/DETC2015-46016

S. Asadi, V. Berbyuk, H. Johansson, *Structural dynamics of a wind turbine drive train high speed subsystem: Mathematical modeling and validation*, In Proc. of the International Conference on Engineering Vibration, Ljubljana, 7 - 10 September; [editors Miha Boltežar, Janko Slavič, Marian Wiercigroch]. - EBook. - Ljubljana: Faculty for Mechanical Engineering, 2015 p. 553-562

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
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, A. Eriksson, A. Kulachenko, M. Mihaescu and G. Tibert (Eds.), KTH, Stockholm, 2014

M. K. Vakilzadeh, V. Yaghoubi, A.T. Johansson, T. Abrahamsson, *Towards an Automatic Modal Parameter Estimation Framework: Mode Clustering*, International Modal Analysis Conference IMAC XXXIII, Florida, USA, February 2-7, 2015

Vahid Yaghoubi, M. K. Vakilzadeh, Thomas J.S. Abrahamsson*, A parallel solution method for structural dynamics response analysis*, IMAC XXXIII, Florida, USA, 2015

M. K. Vakilzadeh, V. Yaghoubi, T. McKelvey, T. Abrahamsson, L. Ljung, *Experiment Design for Improved Frequency Domain Subspace Identification of Continuous-Time Systems*, IFAC, Beijing, China, 2015

M. K. Vakilzadeh, Y. Huang, J. L. Beck, T. Abrahamsson, *Approximate Bayesian Computation by Subset Simulation for Parameter Inference of Dynamical Models*, IMAC XXXIV, Florida, USA, January 25-28, 2016

V. Yaghoubi, M. K. Vakilzadeh, A.T. Johansson, T. Abrahamsson, *Stochastic Finite Element Model Updating by Bootstrapping*, IMAC XXXIV, Florida, USA, January 25-28, 2016

M. K. Vakilzadeh, A. Sjögren, A. T. Johansson, T. Abrahamsson, *Sequential Gauss-Newton MCMC algorithm for high-dimensional Bayesian model updating*, IMAC XXXV, California, USA, Jan. 30-Feb. 2, 2017

A. Mathern, R. Rempling*, Innovative Structural Engineering Approaches for the design of offshore WIND turbine support structures*, Offshore Wind R&D Conference 2015, Research at Alpha Ventus, 13-15 Oct., Bremerhaven, Germany, 2015

A. Mathern, R. Rempling, *ISEAWIND - Innovative Structural Engineering Approaches for the design of offshore WIND turbine foundations*, Vindkraftsforskning i fokus konferens 2015, 6-7 October, Uppsala, 2015

A. Mathern, G. Chantelot, P-O. Svahn et al., *Enhanced strut-and-tie model for reinforced concrete pile caps, 39th IABSE Symposium*. Vancouver, Canada: IABSE, 2017, pp. 607–614

C. Koch, J. Baluku, I. Habakurama, A. Mathern, *The challenges of building inner sea offshore wind farms - the cases of Lillgrund and Anholt*, 9th Nordic Conference on Construction Economics and Organization, June 13-14, 2017, Göteborg, Sweden

H. Abedi*, Influence of generated wind field on Wind-turbine power production in forest Region*, Wind Energy Science Conference 2017, 26-29 June 2017, Copenhagen, Denmark

P. Bangalore, S. Letzgus, and M. Patriksson, *Analysis of SCADA data for early fault detection with application to the maintenance management of wind turbines*, presented at Cigre Session 46, Paris, August 2016

Submitted papers
J. Härsjö, M. Bongiorno, *Analytical and FEM Modeling of a PMSM with a turn-to-turn fault*, Submitted to IET-Electric Power Applications

J. Härsjö, M. Bongiorno *Impact of turn-to-turn faults on the electromagnetic forces in a Permanent Magnet Synchronous Machine (PMSM)*, submitted to IET-Electric Power Applications

N. Espinoza, O. Carlson, *Field-Test of Wind Turbine by Voltage Source Converter,* submitted to Journal of Wind Energy Science

M. Beza and M. Bongiorno, *Identification of resonance interactions in offshore-wind farms connected to the main grid by MMC-based HVDC system*, International Journal of Electrical Power and Energy Systems (under second round of review), 2018

H. Abedi, L. Davidson, S. Voutsinas, *The impact of wind field generation methods on wind turbine power production using Free Vortex Wake Method*, Journal of Wind Energy (under submission process), 2016-2018

S. Asadi, H. Johansson, *Multibody dynamic modelling of a direct wind turbine drive train*, manuscript of journal paper submitted for publication

S. Asadi, H. Johansson, *Global sensitivity analysis a direct wind turbine drive train*, manuscript of journal paper submitted for publication

A. Mathern, C. von der Haar, S. Marx, *Concrete structures for offshore wind turbines: current status, challenges, and future trends*, submitted to Renewable & Sustainable Energy Reviews

Reports
Swerea SICOMP CR17-009 Temperature Sensors in Windmill Blades
Swerea SICOMP CR17-010 Thermography for Inspection of Active Blade De-icing Systems
Swerea SICOMP CR18-005 Methods for replace of electrical cables inside a wind turbine blade
Swerea SICOMP CR18-013 Investigation and long-term testing of blade heating system with dual carbon fiber layers

Master theses
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

Ö. Faruk, H. Mutungi, *Assessment of simulation codes for offshore wind turbine foundations*, Master's Thesis in the Master's Programme Structural Engineering and Building Technology, 2016

I. Habakurama, J. Baluku, *The challenges in installation of offshore wind farms*, A case of Lillgrund and Anholt wind farms. Göteborg: Chalmers University of Technology (Examensarbete - Institutionen för bygg- och miljöteknik, Chalmers tekniska högskola, nr: BOMX02-16-104), 2016

M. Ahlström, C. Holmqvist, *Assessment and comparative study of design method for onshore wind power plant foundations*, Master's Thesis in the Master's Programme Structural Engineering and Building Technology, 2017

E. Ahlgren, E. Grudic, *Risk Management in Offshore Wind Farm Development*. Göteborg, Chalmers University of Technology (Examensarbete - Institutionen för bygg- och miljöteknik, Chalmers tekniska högskola, no: BOMX02-17-61), 2017

J. Isaksson, D. Tenenbaum, *The effect of soil-structure interaction on the behaviour of onshore wind turbines with a gravity-based foundation*, Master's Thesis in Structural Engineering and Building Technology / Master's thesis in Sound and Vibration, 2018

E. Jonsson, E. Tunander, *Alternative evaluation methods for on-shore wind turbines*, Master's Thesis in Infrastructure and Environmental Engineering, 2018

E. Wiklund, *Comparison of structural analysis methods for reinforced concrete deep beams*, Master's Thesis in Structural Engineering and Building Technology, 2018

S. Letzgus, *SCADA-Data Analysis for Condition Monitoring of Wind Turbine Components*, Master Thesis, Dept of Energy and Environment, Chalmers University of Technology, Gothenburg Sweden, 2015

D. Karlsson, *Wind Turbine Performance Monitoring using Artificial Neural Networks*, Master Thesis, Dept of Energy and Environment, Chalmers University of Technology, Gothenburg Sweden, 2015

External activities

International conferences

- The Science of Making Torque from Wind (TORQUE 2016), 5-7 October 2016, Munich, Germany
- Wind Energy Science Conference 2017, 26-29 June 2017, Copenhagen, Denmark
- OpenFOAM Wind power, 13-15 June 2018, Visby, Sweden
- RAVE Offshore Wind R&D, 13-15 Oct. 2015, in Bremerhaven, Germany
- 19th Congress of IABSE, 21-23 Sept. 2016, in Stockholm
- 39th IABSE Symposium, 19-23 Sept. 2017, in Vancouver
- OFFSHORE WIND ENERGY 6-7 June 2017, London
- Seventh GIGAWIND Symposium, March 2017, in Hannover
- Energy Transition 2017, March 2017, in Trondheim

National conferences

- Vindkraftsforskning i fokus konferens, 6-7 October 2015, Uppsala, Sweden
- Energivärlden tema vind, 29-30 May 2018, Stockholm, Sweden
- Maritima Klustret – Västra Götaland, 4 Nov 2015, in Gothenburg
- SOAK 2017, October 19–20, in Linköping, Sweden

Miscellaneous

Meeting and discussion with ABB CR in Västerås within project TG1-2.

Alexandre Mathern has visited research group in Massivbau at Leibniz Universität during March 2017.

Quanjiang Yu participated in a winter school: optimization and operations research, June 2017, in Zinal.

SWPTC organised the conference Vindkraftsforskning i fokus in April 2017 together with the other wind related research programmes in Sweden.

During this period SWPTC has participated at two board meetings within EAWE in Lyngby, Denmark in June and in Cranfield, Great Britain in September 2017.

Mebtu Beza had a one week research visit to Vestas also took place for model verification.

Hamidreza Abedi was visiting National Technical University of Athens (NTUA), from 09-Mar to 03-Apr 2015, Athens, Greece.

Majid Khorsand participated in a four-month visiting program at California Institute of Technology (Caltech) in which the outcomes of this visit are two journal papers and one conference paper.

Pramod Bangalore participated in IEAwind -Task 33 ‘Reliability Data: Standardizing data collection for wind turbine reliability and O&M analyses and also in Nordic Wind Operation and Maintenance (NWOM) meetings.