Annual Report

period 11
2021-01-01 – 2021-12-31

SWPTC
SWEDISH WIND POWER TECHNOLOGY CENTRE

Table of content

Centre

Project title	Swedish Wind Power Technology Centre
Project number	Swedish Energy Agency; P-no: 32591-2, Dnr:2014-002371
Project duration	2019-01-09 – 2022-12-31
Organisation	Chalmers University of Technology, Dept. of Electrical Engineering
Report for	2021-01-01-2021-12-31
Project leader	Ola Carlson (2021-01-01 – 2021-03-31) and Sara Fogelström (2021-04-01 -)
Board members	
Chairman of the board	Elisabet Falemo
Academic partners	Luleå University of Technology, RISE, RISE Sicomp, Lund University, Chalmers University of Technology
Industrial partners	Bulten, Centrica, EnBW Sverige, Energiforsk, Greenbyte, Modvion, NCC Sverige, Rabbalshede Kraft, Stena Renewable, Svk, TensionCam System, wpd

Project description

The two goals of the Swedish Wind Power Technology Centre, SWPTC, are to enhance knowledge of the components and systems, throughout the entire wind turbine and associated systems, to facilitate top-class research with the aim of producing optimum wind turbines and subsystems and of reducing operating and maintenance costs, as well as Swedish development and production of components and subsystems.

In the first stage of SWPTC, knowledge was built up about wind turbines among the participating academic partners, from expert knowledge in their respective fields to their application to wind power. This could then be further developed in stage two, where more in-depth research was carried out and links were also established between the areas of expertise. This development is intended to continue in the third stage with several cross-disciplinary projects.

The focus of activity in SWPTC is on knowledge for technology development and the efficient operation of wind turbines, since this is very important for cost-effective electricity generation, which needs to be adapted to the natural sites in Sweden. The adaptation of the power electronics of wind turbines to the Swedish electrical system is also important for a stable power grid. A further important characteristic of a competence centre is its critical mass and this is particularly applicable to wind power technology which encompasses several technical areas of expertise.

The research carried out at SWPTC is mainly aimed at the individual wind turbine, since it is essential to first understand how its individual parts work together to ensure the optimum conversion of wind energy to electrical energy. Today's view that a group of wind turbines can be equated to a power plant shows the importance of having good knowledge of the interaction between wind turbines in a wind farm and the best way to control and link these together to maximise electricity generation and obtain the best service life. The research will focus on large wind turbines and wind farms to be sited in forest, mountain and offshore environments.

SWPTC has identified six research areas that stage 3 will focus on. These are Supporting Structure, Electric Drive Train and DC grids, Lifetime and maintenance, Deicing and ice detection, Forest/Complex terrain and control as well as Grid service from wind turbines.

In order to develop the research areas and address various problems, in-depth knowledge of different areas of expertise is required. The different areas of expertise which form the basis for wind power technology are described in the next chapter. These areas are Electric Power Engineering, Fluid Dynamics, Automatic control, Dynamics, Structural Engineering, Materials Technology and Numerical Analysis and Optimisation

The projects in SWPTC are carried out in close collaboration with industrial partners to facilitate the utilisation of the research findings. The role of industry in a project may include many different elements, everything from proposing and writing project applications, taking an active part in calculations and the analysis of results, delivery of measurement data, component and operational data, description of a plan for a service contract, to participating in a doctoral student's reference group.

At Chalmers there are five divisions active in SWPTC; Electric Power Engineering, Dynamics, Fluid Dynamics, Structural Engineering and Mathematics. The units Renewable Energy from the Ocean and Wind, Building and infrastructure and Transport safety at 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

Now more projects have been started during this period since all available funding has been allocated in projects and operation. All ongoing projects are broad and include at least two areas of expertise. The project portfolio covers four of six research areas of the programme description.

At the end of the reporting period, the Centre projects employ two post docs, nine researchers and three senior researchers. Another four senior researchers are connected to the Centre but are not working directly in a project. Around 20 people from the industry partners also work with SWPTC projects. During this period the Centre has generated about 24 full-time equivalent of work.

Finances

At the end of the report period, the Centre has received just over 18 000 kSEK in cash, whereof 66 % comes from the Swedish Energy Agency, 19 % comes from industry partners and 14 % from the academic partners. The total cash budget for whole duration of stage 3 of SWPTC is 24 million SEK.

During this period, no new projects have been started since the whole budget for SWPTC is allocated in project and operation. The four previously approved projects have continued their work. The work is divided between four senior projects where one project included a PhD project.

Up to and including this period, the industrial companies have carried out 97 % of their total share of in-kind, and the academic partners have carried out 77 % of their total share of in-kind. During the whole of stage 3, 24 million SEK of in-kind work will be carried out.

For more details about the finances of the Centre's, see the financial report.

Other internal activities

During this period SWPTC has had four Advisory Board meetings.

Deviations from project plan

Two projects are redoing their project plans and this may affect the outcomes of the project. The new project plans will be available during quarter 1 2022.

Publications during this period

One doctoral thesis and two journal papers were published during this period. Further, three more papers has been submitted to journals and conferences.

External activities

During this period SWPTC has participated at two board meetings within European Academy of Wind Energy (EAWE), in May and in November. EAWE has also held to strategy committee meetings that SWPTC has participated in. SWPTC has initiated the work with starting up a new technical committee within EAWE regarding test wind turbines. SWPTC has also joined the Diversity committee in the Academy.

SWPTC has also participated in two board meetings within European Energy Research Alliance (EERA), in May and in September.

Methods and material for sustainable and cost effective structural supporting systems for wind power plants

Project title	Methods and material for sustainable and cost effective structural supporting systems for wind power plants
Organisation	RISE, Chalmers University of Technology
Project leader	Anders Wickström, RISE
Other participants	Rasmus Rempling, Chalmers, Hamidreza Abedi, Chalmers, Jesus Armesto Barros, NCC, Nilla Olsson, NCC, Alexandre Mathern, NCC, Tobias Larsson, NCC, Erik Dölerud, Modvion, Carl-Johan Åkerström, Modvion, Geir Söderin Modvion, Jonas Nilsagård, TensionCam
Report for	2021-01 01– 2021-12-31
Participating companies	NCC, Modvion, TensionCam Systems, Rabbalshede Kraft, Stena Renewable

Project description

The overall purpose of this project is to increase the knowledge of tomorrow's supporting structures and to aid business development in Swedish wind power and construction sectors. With this project, the sectors will come closer to delivering solutions that are more cost-effective, with a less impact on the environment and minimal maintenance. The results will extend the life of wind turbine towers and foundations by better load predictions and load control.

It will also propose specific solution aspects where wood is the base material in turbine towers. Towers built in laminated wood has a potential to reduce manufacturing costs to 40% lower cost than the corresponding tower in steel and minimizes environmental impact. This project will provide clarifications on potential risks, by validations from the new Chalmers pilot research turbine at Björkö and by additional analyses and laboratory tests. Further a reliable connection to the (concrete) foundation will to be invented, tested and evaluated for an optimal full-scale 150 meters wood tower.

Methods for measurement of pretension in bolts do exist but are for various reasons not used on a general basis. With better and cheaper control of pretension, a bolt joint design can be optimised with downsizing of both the bolt itself as well as the surrounding components. This project will provide a documented and validated methodology to control and supervise pretension in tower bolt connections.

Results

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

WP2: Numerical simulations of complex terrain

The purpose is to study and assess in detail, by simulations, different loading conditions, tower heights and material compositions in tower and foundation; as well as, cross-sectional forces in critical sections of the tower-nacelle attachment, tower-foundation anchoring and hot-spots for fatigue in tower and foundation.

During 2021, an assessment of the different stiffness conditions for a steel versus a timber tower has been started as an extra investigation. It is based on previous work in WP2. Two FAST-models have been developed, one for the timber tower "Björkö-tower" and one for an equivalent steel tower. The models include several different characteristics for the steel and timber models with the main difference in global stiffness. Based on the analyses made in FAST, sets of sectional forces acting on the foundation have been extracted by a developed MatLab code. By means of the developed design tool in WP3, analysis have been made on the basis of similar power output, i.e. the analyses are based on supporting structures (foundation-tower) that generate the same power output with the same turbine. Early results show that to reach an equivalent global stiffness between the timber and steel supporting structure the timber-tower base needs to be larger than the steel-tower base. The larger base results in a larger concrete foundation and use more reinforcement steel, which in turn results in a very much higher climate impact due to the larger amount material used for the foundation. Another early result shows that the larger timber-tower base causes a higher excitation on the coupling between the foundation and tower base, which results in higher fatigue actions on the foundations. The higher fatigue loads make the foundation aging faster. To counteract this degradation more reinforcement is needed, which results in a higher climate impact.

The scope of WP2 does not include further investigation of the above-mentioned phenomena and further investigations will depend on available budget.

WP3: Product and Processes

The design, construction and management of wind power plants are essential areas when it comes to promote national up-scaling of the wind power as an energy source. The purpose of this work package is to investigate solutions that are cost-effective in all three areas and the following activities are planned:

- Identify a generic design tool that can design with regard to sustainability and buildability aspects of foundation and tower.
- Investigate the degradation of concrete foundation and how this degradation can be slowed down by a better design and construction process.
- Investigate Stakeholders' needs of a monitoring system of tower and foundation.

The research in WP3 has focused on multi-objective optimization in order to optimize the structural design of wind turbine foundations with regard to sustainability and buildability objectives. To do so, methods for parametric structural design based on finite element analysis, multi-criteria assessment, and multi-objective optimization have been implemented. The structural design is conducted in accordance with Eurocode requirements as well as other requirements from turbine manufacturers. The proposed method led to an improvement by 8-15% of the designs for the foundations developed in practice in terms of the sustainability indicators considered. The results have been published in open access in the journal Structural and Multidisciplinary Optimization.

A study to investigate the evolution of onshore wind turbines and its consequences on the design and climate impact of gravity foundations built in the last 10 years has been conducted. For that, data from Swedish wind farms set in operation between 2013 and 2022 has been analysed. The evolution of turbine size, foundation dimensions, reinforcement layout, material types and quantities, and embodied carbon have been analysed and will be summarized in an article that will be presented at a conference in 2022.

The study of defects and degradation of concrete foundations and their relation to design and construction aspects has been done in collaboration with WP4 and presented in an article submitted to the open access journal Applied Sciences. The results are described under WP4

Potential improvements in the life-cycle performance of wind turbine foundations in design, construction, operation, maintenance and monitoring, and end-of-life have been studied in collaboration with WP4 in a series of interviews. The results are being analysed and summarized in a paper that will be presented at a conference in 2022.

WP4: Intelligent supporting structure

The purpose of this work package is to investigate monitoring systems that can act as an intelligent agent for stakeholders.

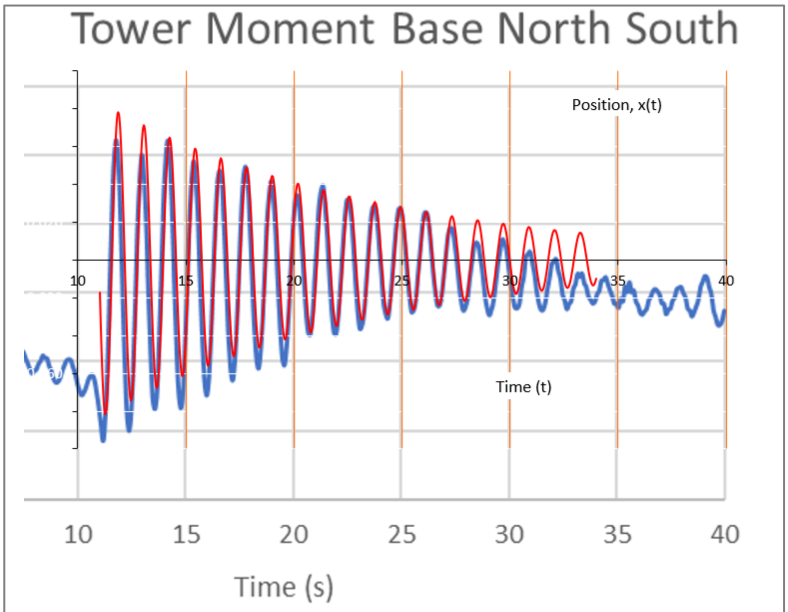
The work within this work package was initiated January 2020 and a detailed activity plan was done in cooperation with the other work packages. With the objective to enable a cost-effective solution that require a minimum of maintenance, the first activity was an interview study with stakeholders. The purpose was to gather knowledge about wind power foundations and especially about design issues, construction process, and sustainability and durability aspects. The interviewees have been involved in several wind turbine projects. They were identified to represent different positions, at different stages in construction and maintenance, different companies, and both research and development.

The results from the interviews have been analysed and are being summarized in a paper for Nordic Concrete Research, XXIV NCR Symposium 2022. The results show that problems with foundations are not uncommon, and that the underlaying cause of the problems are often not understood or monitored. It was also highlighted that there is a lack of relevant data related to the problems from both construction and operation to analyse the problems.

In the next phase of this work package, a case study was performed to investigate commonly occurring problems in foundations related to the production phase of foundations. The cause of the problems was analysed. The personnel involved in the works appears to have a clear influence on the quality achieved and the production time. The study highlights that monitoring from construction and inspection is important to achieve good quality control and to increase knowledge to design and deliver foundations with higher quality. This study is summarized in a journal publication submitted to the open access journal Applied Science.

WP5: Innovative wood tower
The purpose is to increase the knowledge of wooden wind turbine towers in order to prove that wooden towers are commercially viable alternatives to conventional steel towers. This includes to investigate innovative design solutions to avoid a steel transition piece between the wooden tower and foundation and to increase knowledge of fatigue strength properties of wood and joints by laboratory tests. Measurements and feedback from the Chalmers wind turbine at Björkö will be used for experiments and validation.

As the pilot tower is now up and running, tests have been executed on the real tower. Results include damping properties, which are difficult to calculate. Some results are shown below. Tower bending moment has been analysed from tests where the tower was prestressed and released (blue line), see Figure 1. Corresponding analytic response has been plotted in red on top. The parameter values are printed in Figure 1 as well. The good damping properties has been validated.



Natural frequency	f_n	0.84	Hz
Relative damping	x	0.015	
Dampning constant	D	0.16	kg/
Logaritmic decrement	d	0.094	
Stiffness ratio	K/M	28	s^2
Damping ratio	D/M	0.159	1/s

Figure 1 Tower damping of Björkö-tower

The resonance phenomena at 50 rpm have been validated, see Figure 2. It is probably not only the 1P resonance but also 3P which seems to trig the torsional resonance at 50 rpm. This is a phenomenon which is not often seen at tubular steel tower as they are stiffer in the torsional direction. This resonance has been discovered during the further dynamic investigation, which is a task of the project.

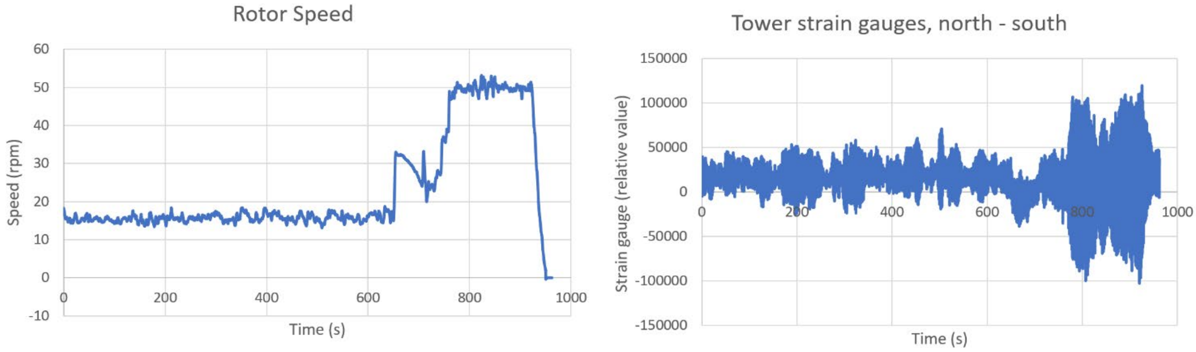


Figure 2 Resonance phenomena at 50 rpm

By considering four expected frequencies and tune the analytical parameters to follow the corresponding measurements at 66 rpm, relatively good agreement is shown in Figure 3. This is near the rated rotor speed 75 rpm and not expected to be problematic from a dynamic point of view.

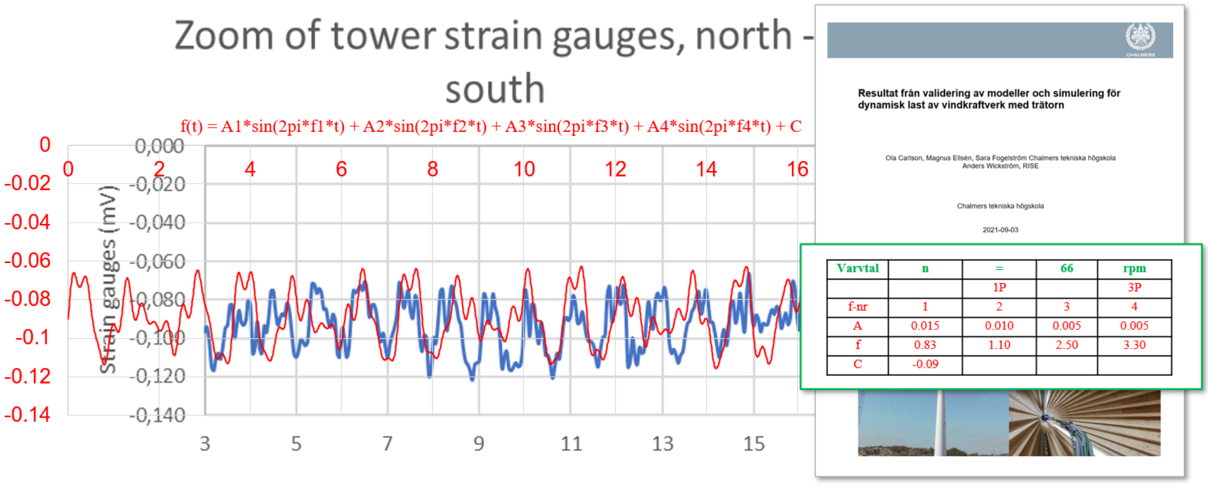


Figure 3 Tuning of analytical parameters to match measurements

However, decreasing the rotor speed to 50 rpm, a more periodical pattern is shown explaining the resonance phenomena at this rotor speed, where 1P bending and 3P torsional both are trigging the dynamic motions see Figure 4.

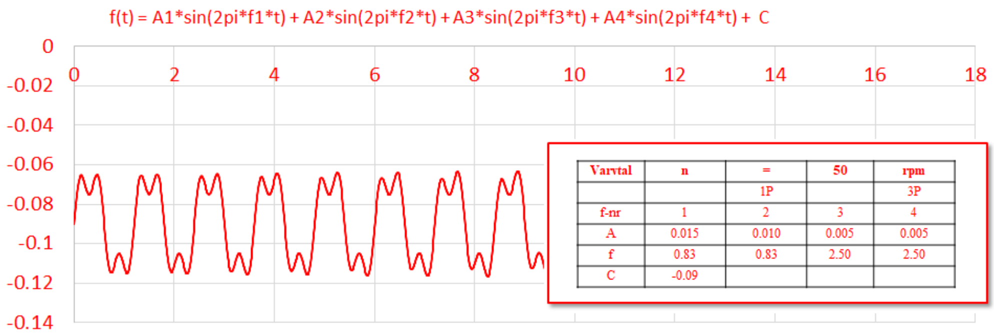


Figure 4 1P and 3P are triggering a dynamic motion

Two different principles to connect the wooden tower to the concrete foundation have been presented and investigated.

1. To connect the wooden fixed steel plates permanently into the concrete foundation, left in Figure 5
2. To use a bolt connection, right in Figure 5.

Eventually one base concrete sample can be used for workshop tests of both principles. These tests are planned to be executed during 2022.

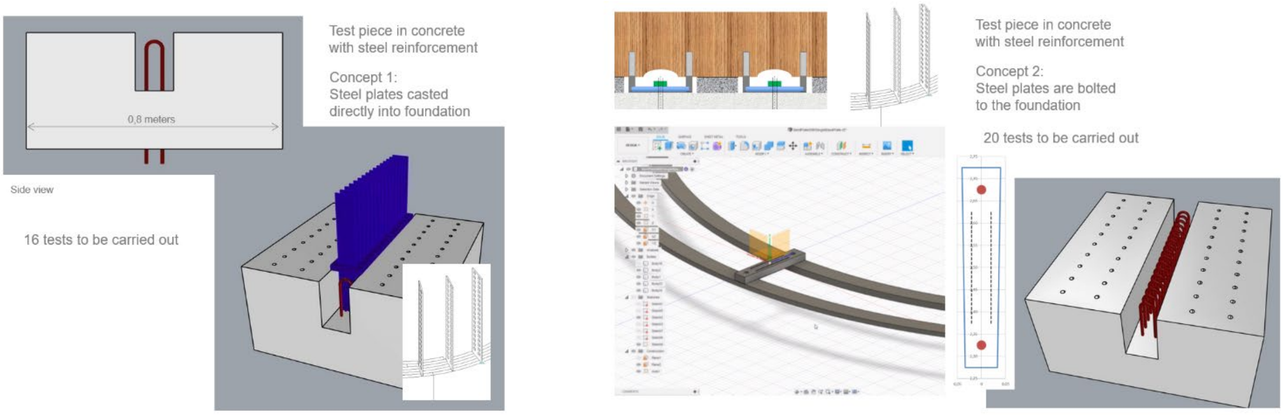


Figure 5 Two different principles to connect wooden tower to concrete foundation

WP6: Methods for supervision of bolt pretension
This work package was finished already in 2019.
An extension has been started, which is presented in a separate project.

Fulfilment of SWPTC's goals

The project contributes to the following goals of the Centre:

- Top-class research with the aim of producing optimum wind turbines subsystems, reducing operating and maintenance costs
    - Yes, this research project has involved several areas of expertise.
    - The development of the design tool in WP3 is expected to help minimizing material use and designing in a way that improves buildability and therefore reduces material costs. The tool helps finding optimal values for preliminary design and it is expected that it will soon optimize with more thorough checks.
- Swedish development and production of components and subsystems
    - Yes, all partners are Swedish companies.
    - The work in WP3 has increased the NCC knowledge on wind turbine foundation design. At the same time, the tool will help in finding more sustainable and less expensive designs that will make NCC more competitive against other international actors.
    - The work in WP5 has increased the Modvion knowledge on structural integrity of different glue connected wooden parts and further knowledge of structural dynamic behaviour.
- An extended service life with the aid of better load prediction, optimum operation and preventive maintenance.
    - Yes, the work on the design tool in WP3 reveals different and important aspects of the design of a foundation. Arising questions about how to lay the reinforcement or ratios between different dimensions, among others, increase the knowledge on the structural supporting system.
- The development of maintenance methods, including fault detection, based on operational data in collaboration with design data.
    - Yes, based on the interview study with stakeholders, knowledge about wind power foundations and especially about design issues and the construction process, will lead to decreased maintenance needs.
- Reliable wind turbines resulting in a high uptime in a cold climate, in forests and offshore.
    - Yes, the purpose of the project is to increase reliability of wind turbines, with higher availability, in any environmental condition.

Deviations from project plan

WP5: The project has been delayed in general for several reasons. Workshop tests of potential foundation options has been rescheduled to 2022 due to corona restrictions. Also other activities have suffered from lack of physical meetings. Further there have been resource constraints due to other projects and parental leave. Therefore, a detail plan is under development in order to finalize the project according to the plan in 2022.

Publications

A. Mathern, V. Penadés, J. Armesto Barros, V. Yepes, *Practical metamodel-assisted multi-objective design optimization for improved sustainability and buildability of wind turbine foundations*, Structural and Multidisciplinary Optimization, accepted 2021-12-10

J. Armesto Barros, A. Mathern*, Recent and future trends of onshore wind turbine foundations*, submitted to IABSE Symposium Prague 2022 - Challenges for Existing and Oncoming Structures, May 25-27, 2022, Prague, Czech Republic (2022)

A. Mathern, J. Magnusson, Lessons learned from the construction, inspection, and defect assessment of reinforced concrete foundations for wind turbines, submitted to Applied Sciences.

External activities

No externa activities during this period.

Miscellaneous

Lecture was held at Chalmers including results from this project: *Resultat från validering av modeller och simulering för dynamisk last av vindkraftverk med trätorn*, Chalmers, 2021-10-06.

Site-Adaptive Analysis Methods to Predict and Enhance Lifetime of Wind Turbines

Project title	Site-Adaptive Analysis Methods to Predict and Enhance Lifetime of Wind Turbines
Organisation	Chalmers: M2 Dynamics, M2 Fluid Dynamics and Applied Mathematics
Project leader	Håkan Johansson
Other participants	Hamidreza Abedi, Quanjiang Yu, Saptarshi Sarkar, Serik Sagitov, Sara Fogelström, Chalmers, Pramod Bangalore, Greenbyte
Report for	2020-01-01 – 2020-12-31
Participating companies	Greenbyte, Rabbalshede Kraft, Stena Renewable, EnBW Sverige

Project description

The project considers the sequence “from wind to fatigue life”, and by simulation investigate how the site-specific conditions (terrain, forest, etc.) affect the fatigue life of turbines. The project involves CFD simulations to investigate the flow field, wind turbine system simulations to evaluate how this flow field affects wind turbine operation and lifetime of drive train components, and development of maintenance algorithm to reduce down-time and repair waiting time.

More specifically, to investigate the flow field in complex terrain, an advanced numerical method is developed to investigate how the site-specific conditions (terrain, forest, etc.) affect the fatigue life of turbines. For this purpose, CFD (Computational Fluid Dynamics) will be carried out in a region of 10x10 square km surrounding the wind farm. Advanced CFD simulations (Large Eddy Simulations) give the fluid flow around each wind turbine in the wind farm located in complex terrain with heterogeneous forest. The commercial CFD software STAR-CCM+ will be used to model the airflow. The local flow field around the wind turbines will be fed into an open-source CAE tool called FAST (Fatigue, Aerodynamics, Structures and Turbulence) by which electric power production and fatigue loads can be computed. The wind conditions at the site will be taken from the meteorology mast and SCADA data from the wind turbines. The Röbergsfjället wind plant located in Dalarna is used in this project. The topology and the forest density of the site (Röbergsfjället) are obtained from Laser data (LAS file) from SLU. It is very hilly, partly covered by forest and consists of 8 2MW Vestas machines.

To investigate turbine fatigue life under varying loads, a previously developed system simulation model of a 2MW turbine is used to determine the drive train loads. To assess the internal drive train loads and estimate fatigue life of drivetrain components, a generic gearbox model is developed and studied.

Results

The Röbergsfjället site of 8 wind turbines located in complex terrain is used as a study object. The wind profiles, as well as mean flow and turbulent kinetic energy profiles, have been extracted from CFD simulations. In contrast to earlier work, the CFD simulations are done with and without consideration of turbine interaction (actuator disk model) with the flow field. It was found that the CFD predicted downwind effect from turbines, in terms of reduced mean wind speed and increased turbulence, match the operational experience from SCADA reasonably well. Change in wind speed or wind direction did not cause any substantial changes in the characteristics of the predicted wind fields.

In order to quantify the wind field effect on turbine dynamics and internal loads, a system simulation model of a 2MW turbine in FAST representative of the turbines at Röbergsfjället site developed in earlier work was used. A gearbox model was implemented in the simulation software SIMPACK and integrated in the FAST model of the turbine. A measure to evaluate the risk of roller slip in bearings was proposed. The measure is intended to identify situations of high rotational speed and low of torque, conditions that are known to cause bearing faults (e.g. smearing). Analysing different operational conditions has found that grid faults and emergency stops are likely to cause instances of bearing slip in the high-speed stage of the gearbox. This risk was shown to be much higher for faults occurring at low winds, which can be expected more frequent in high-turbulence medium-wind sites. It was found that synthetic wind fields (generated by Turbsim tool) can predict the same gearbox fatigue loads and risk for bearing slip as the CFD simulations. However, it was also found that the synthetic wind model must be adapted to the particular mean wind and turbulence of the place of the turbine, which can vary noticeable within the site. This variation within a site can be predicted by CFD simulation but is difficult to catch with a single met mast.

During this period Quanjiang Yu finished his PhD project that was part of this broader project. The work during 2021 focused on short-term planning of preventive maintenance time schedules. The developed optimization models adopt realistic assumptions and can be accurately solved in seconds. One of the developed frameworks for short-time planning was further extended so that available condition monitoring data could be incorporated for regular updates of the components' hazard functions. The model was tested with data from a wind farm and the case study demonstrated that this framework may result in remarkable savings due to smart scheduling of preventive maintenance activities by monitoring the ages of the components as well as operation data of the wind turbines.

Fulfilment of SWPTC's goals

The project aims at better prediction of wind turbine loads by considering also the particular site the turbine is operating. The project results so far address the SWPTC goals as follows:

- An extended service life with the aid of better load prediction, optimum operation and preventive maintenance.
    - Better prediction of wind turbine loads by more accurate wind field analysis considering the complex terrain.
- The development of maintenance methods, including fault detection, based on operational data in collaboration with design data.
    - Developed generic gearbox helps development of fault detection methods and evaluation of operation data
    - Developer algorithm and maintenance models enables further studies to develop a and efficient predictive maintenance scheme that is implementable on today's turbines.
- Reliable wind turbines resulting in a high uptime in a cold climate, in forests and offshore.
    - Improved understanding of wind conditions in in forest regions (which typically have also complex terrain) helps improving turbine operation.
    - The project address improved lifetime predictions based on detailed drivetrain analysis, better load prediction by more accurate wind field analysis considering the complex terrain, and predictive maintenance by better maintenance scheduling tools

Deviations from project plan

The late arrival of Post-Doc prompted a revision of the time-plan. The end time of project has been postponed to June 2022.

Publications

Q.Yu, *Cost optimization of maintenance scheduling for wind turbines with aging components*, Ph.D. thesis, Chalmers University of Technology, 2021

Q. Yu, M. Patriksson, S. Sagitov, *Optimal scheduling of the next preventive maintenance activity for a wind farm*, Wind Energy Science, Vol. 6 issue 3 p. 949-959, 2021

H. Abedi, S. Sarkar, H. Johansson, *Numerical modelling of neutral atmospheric boundary layer flow through heterogeneous forest canopies in complex terrain (a case study of a Swedish wind farm)*, Renewable Energy, Vol 180, 806-828, 2021

External activities

Saptarshi Sarkar presented "Site-specific analysis of wind turbines in complex terrain: A case study" at Wind Energy Science Conference (WESC) 2021 25-28 May, co-authored with Hamidreza Abedi, Håkan Johansson and Viktor Berbyuk

Extension of WP6 Methods for supervision of bolt pretension

Project title	Extension of WP6 Methods for supervision of bolt pretension
Project number	
Organisation	RISE
Project leader	Anders Wickström
Other participants	Others from RISE: Johan Sandström, Göran Malmqvist, Alice Moya Nunez, Rikard Norling, Jakob Blomgren, Kaies Daoud och Fredrik Ahrentorp From Chalmers: Magnus Evertsson
Report for	2021-01-01 – 2021-12-31
Participating companies	TensionCam Systems, Bulten, Rabbalshede Kraft, Stena Renewable

Project description

Methods for measurement of pretension in bolts do exist but are for various reasons not used on a general basis. With better and cheaper control of pretension, a bolt joint design can be optimised with downsizing of both the bolt itself as well as the surrounding components. This project will provide a documented and validated methodology to control and supervise pretension in tower bolt connections.

Results

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

WP1 Validations by laboratory tests, field measurements and FE-analyses
This work package was finished already in 2020.

WP2 Environmental resistance
This work package was finished already in 2020.

WP3: Remote reading of bolt status
This work package was finished already in 2019.

WP 4: Scientific aspects, optimization and documentation
The aim of this work package is to write a scientific paper. The aim is further to investigate the potential for optimization of bolt connections, based on the possibility to have an improved pretension control, i.e. a narrower distribution of actual individual bolt pretension value. Recommendations on the design aspects, on how to actually dimension well working and robust bolted joints, including the tightening and monitoring procedures will be proposed based on the conducted research work.

On December 24, 2015, a wind turbine collapsed in Lemnhult, Sweden. The wind turbine that fell was 129 meters tall and had a turbine diameter of 112 meters. The wind turbine had been in operation for almost three years. The bolt joint in the first flange failed and the upper part of the tower fell. The bolts that had held together the joint had suffered from a fatigue process and the bolts could no longer withstand the loads of normal operation. This paper analyses a typical traditional tower flange bolt joint, see Figure 6, exposed to cyclic loads from normal operation. A modification of the joint design is proposed where a sleeve is introduced in order to improve the stiffness ratio. The results are presented and compared to the traditional design.

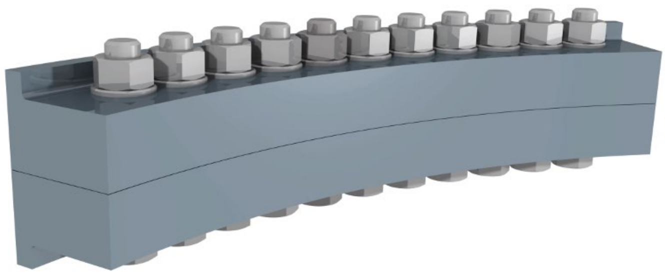


Figure 6 Traditional tower flange bolt joint

A generic wind turbine, 112 meters diameter and rated power 3 MW, has been modelled in the aero elastic simulation tool VIDYN. Public data of the Vestas V112 has been used to tune the model. The turbine control algorithms are copied from the open NREL. The parameters are adjusted to the size and rating of the turbine.

For design load calculations, according to the standard, each mean wind speed between 4 and 25 m/s has been simulated for 10 minutes with a turbulence intensity TI = 16 %, corresponding to turbine class A. The first 40 seconds are skipped to avoid high loads caused poor initial conditions. A Weibull function, with parameters A=8.46 m/s and C=2, corresponding to mean wind speed 7.5 m/s and turbine class 3, has been used to provide probability numbers for each mean wind speed.

The average thrust force follows a parabolic function at low wind speeds up to rated wind. When pitch control starts, the thrust force decreases as only a fraction of the available wind power is used to keep the power constant. Both the short term thrust force variations, caused by turbulence, and the long-term variations, caused by wind speed changes over time, lead to cyclic fatigue loads in the tower structure.

The work package has calculated the equivalent bending moment for 20 years life at a specific height of the tower has been calculated. This has then been used to calculate the total maximal external force on a bolt in the flange. The total maximal external force on a bolt in the flange is the sum of the contribution from the bending moments and the normal force.

To connect the two tower sections at the specific height, two different flange connections have been analysed and compared in terms of fatigue resistance. The theory of prying effect in L-flange joints and effects of using sleeves have been accounted for:

1. CASE 1 is a “traditional” bolt flange connection of 100 M64 bolts
2. CASE 2 is a “new” modified flange of 148 M42 bolts with sleeves.

The results show that the proposed new CASE 2 design has half the weight compared to CASE 1 but the structural integrity in terms of fatigue in the bolts are still higher in CASE 2, thanks of the sleeve. This might change how the future bolt connections look like, not only in wind applications but also general tubular bolt connections. Some additional sensitivity analyses have been executed. It is shown that the depth has a very large impact on the bolt fatigue strength. In a comparison, the depth has decreased from CASE 2, equal to 0.232 m depth down to 0.172 m. The bolt integrity decreased with lower flange depth as the Stress Reserve Factor decreases from 1.74 down to 0.58. At a depth larger than 0.228 m, the 148 M42 bolts provide a higher structural integrity than the 100 M64 bolts. If the depth goes below 0.19, the SRF < 1 which means that the bolt life is less than 20 years.

These findings have a potential to change the future bolt connection design from large bolts to slender bolts supported by sleeves. The potential is that the amount of material in the flange can be reduced to half of the traditional bolt connection.

Fulfilment of SWPTC’s goals

The high level SWPTC’s goals are listed below followed by comments on fulfilment in this specific project.

- Top-class research with the aim of producing optimum wind turbines and subsystems and of reducing operating and maintenance costs.
    - Yes, this research project has involved several areas of expertise. A number of experienced researchers at RISE have cooperated and worked within their fields of expertise to obtain the successful project results.
- Swedish development and production of components and subsystems.
    - Yes, all partners are Swedish companies
- An extended service life with the aid of better load prediction, optimum operation and preventive maintenance.
    - Yes, the purpose of the new innovative product is controlling the bolt pretension in order to execute preventive maintenance for optimum operation.
- The development of maintenance methods, including fault detection, based on operational data in collaboration with design data.
    - Yes, the purpose of the new innovative product is fault detection, based on data from the installed sensors.

- Reliable wind turbines resulting in a high uptime in a cold climate, in forests and offshore.
    - Yes, the purpose of the project is to increased reliability of wind turbines, with higher availability, in any environmental condition

Deviations from project plan

The scientific paper is not finished or published yet. The plan is to send it to Wind Energy Science in the spring 2022.

Publications

No publications during this period.

External activities

No external activities during this period

Frequency services from wind power in the Swedish power system

Project title	Frequency services from wind power in the Swedish power system
Project number	
Organisation	Electric Power Engineering, Chalmers University of Technology
Project leader	Ola Carlson
Other participants	Håkan Johansson, Viktor Berbyuk, Saptarshi Sarkar, Magnus Ellsen, Sara Fogelström at Chalmers, Mattias Persson, Camille Hamond at Rise
Report for	2021-01-01 – 2021-12-31
Participating companies	Rabbalshede Kraft, Stena Renewable, Centrica, Svenska Kraftnät, Energiforsk,wpd

Project description

There is a strong expansion of wind power in the Swedish electric power system and future scenarios indicate that wind power will be a dominant source of power during windy periods as early as 2022. An important part of the electricity grid's stability is that the frequency (50Hz) is maintained. Today, mainly hydropower plants are used to do this. In the future power situation, it is of great importance that wind turbines are also used to keep the frequency stable. The project will develop, simulate and test frequency control with wind turbines. The standard built-in frequency control will be tested in commercial wind turbines and the plants will also participate in the bidding of ancillary services. Furthermore, existing frequency control services will be tested and developed at Chalmers wind turbine. The technical function and demand for wind turbines to control the frequency in the electricity grid will be verified and evaluated. This also includes analysis of wear and how the lifetime of the pitch system and gearbox is affected. The results will also show the economic potential of wind power operators to participate in the frequency regulation market.

During the period a new industry partner has joined the project: wpd

Results

The previous developed models in the project have been further developed during this period. Some results from the simpler model can be seen Figure 7. In the figure it can be seen that the turbine speed goes down at time 120 s. This is a consequence of that the turbine is producing extra power. This is a simple representation of FFR.

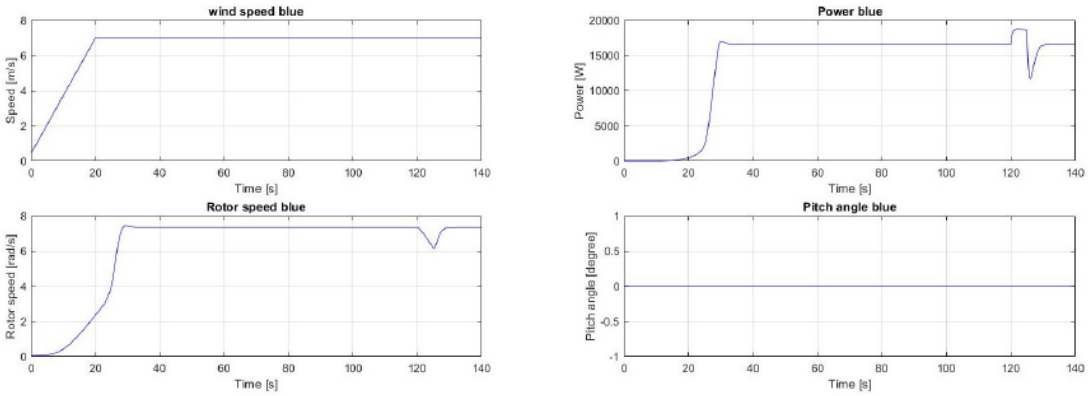


Figure 7 Simulations by simple model of wind turbine during FFR-operation.

In Figure 8 the operation of the turbine is set to limit the power output to 15 kW. As a result, it can be seen that the pitch activities increase quite a lot. How this increased pitch activities influence the maintenance will be further investigated. The simulations are carried out with the more advanced model in Ashes.

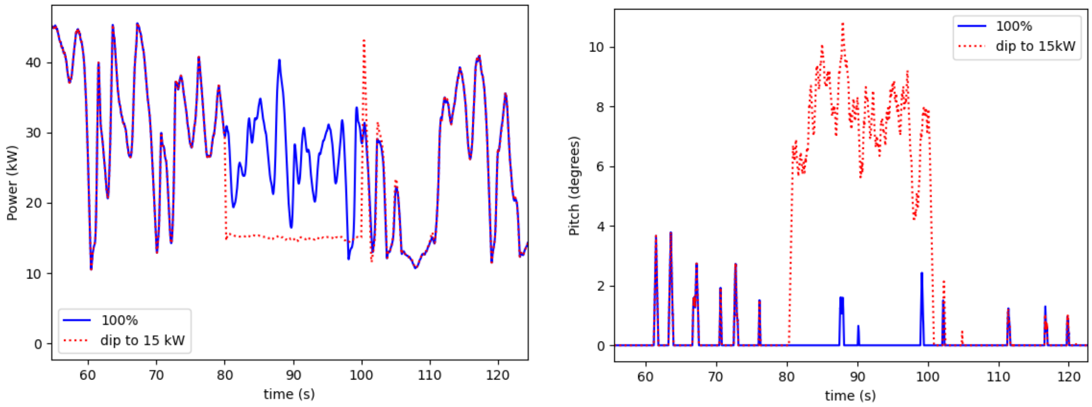
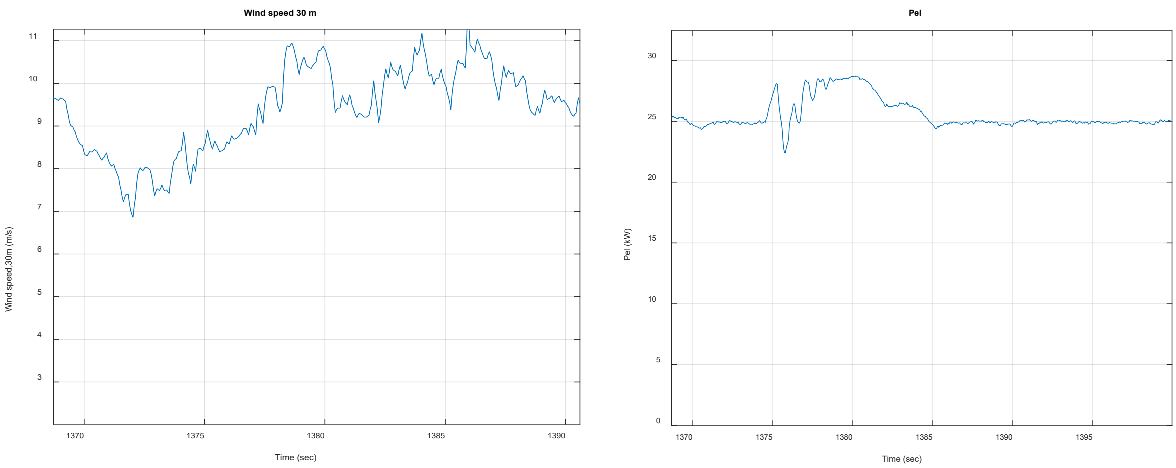


Figure 8 Simulations by advanced model of wind turbine during curtailment.

RISE has continued and almost finished its work regarding the economic outcome of different bid strategies for frequency services. Yearly income from participating in different ancillary service markets for a 2 MW wind power plant has been evaluated for different cases related to the impact of forecasting errors. The cases included, perfect foresight on minute basis, perfect foresight on hourly basis, average considering forecasting errors available in literature and finally a case with twice the forecasting errors as previous. The total for each ancillary service and case has been calculated as both absolute value in EUR and percentage of the day-ahead only revenues with perfect foresight on minute basis. The income has been computed and split into day-ahead and ancillary services income. From the results it can be seen that aFFR down + day-ahead is the single most profitable service for the studied case. However, if a switching between services based on ideal price prognosis for the various services was available a large increase in earnings could be achieved.

Frequency control with all suitable frequency support services, developed earlier in the project, has been tested in real operation on Björkö at Chalmers wind turbine. Figure 9 shows measurements from a FFR tests at the turbine. At time 1375 sec the power is increased from 25 to 29 kW, the pitch is decreased to maximum power setting and the speed decrease a bit. After the power boost the turbine goes back to normal operation quite soon. In this test the boosted power is added on top of the normal power settings. This is however creating some power fluctuations in the beginning of the boost period.



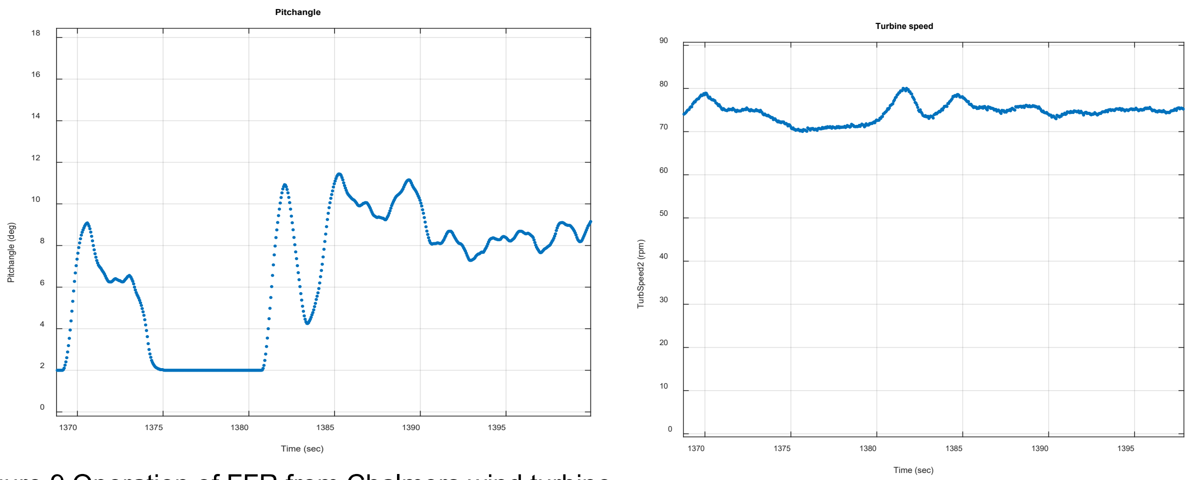


Figure 9 Operation of FFR from Chalmers wind turbine

The work with frequency control with the most appropriate frequency support services will be tested in real operation on a 2-5 MW wind turbine is in progress. During this period three different wind farms have been identified to be most suitable. The carried work also included clarification of the operation and communication requirements for the wind turbines. Also, legal issues have been a part of the work. How measurements and evaluation of the operation should be done have been discussed between Chalmers and the industry partners.

Fulfilment of SWPTC's goals

The project fulfills the following of SWPTC's goals:

- Top-class research with the aim of producing optimum wind turbines and subsystems and of reducing operating and maintenance costs.
- An extended service life with the aid of better load prediction, optimum operation and preventive maintenance.
- Reliable wind turbines resulting in a high uptime in a cold climate, in forests and offshore.

The goals will be fulfilled by:

- Showing the economic outcome for the wind turbine operator when wind turbines participate in frequency control compared to producing only electric power.
- Presenting and evaluating the frequency support services used internationally.
- Developing and optimising the operation of a wind turbine during the provision of frequency support services.
- Developing, testing and demonstrating frequency support services at Chalmers wind turbine.
- Providing frequency support services in the operation of a commercial wind turbine and a wind farm.
- Explaining the change in lifetime of turbine, by using load calculations during frequency support services in a wind turbine.

Deviations from project plan

The project is late regarding the simulation modelling but are estimated to reach the goals for the project during 2022. It has also been slow progress in finding available wind turbines to take part in frequency control. The first wind farm will soon be available, but the number of turbines will be lower than planned. There will also not be as much time for real time testing as planned, but this will hopefully not affect the project outcomes.

Publications

A conference paper has been submitted:
Possible wind farm earnings from frequency regulation markets in Nordic power system, Camille Hamon, Mattias Persson, Cigré Session 2022

External activities

No external activities during this period.

Publications

Doctoral theses

Q.Yu, *Cost optimization of maintenance scheduling for wind turbines with aging components*, Ph.D. thesis, Chalmers University of Technology, 2021

Journal papers

H. Abedi, S. Sarkar, H. Johansson, *Numerical modelling of neutral atmospheric boundary layer flow through heterogeneous forest canopies in complex terrain (a case study of a Swedish wind farm)*, Renewable Energy, Vol 180, 806-828, 2021

Q. Yu, M. Patriksson, S. Sagitov, *Optimal scheduling of the next preventive maintenance activity for a wind farm*, Wind Energy Science, Vol. 6 issue 3 p. 949-959, 2021

Submitted papers

A. Mathern, V. Penadés, J. Armesto Barros, V. Yepes, *Practical metamodel-assisted multi-objective design optimization for improved sustainability and buildability of wind turbine foundations*, Structural and Multidisciplinary Optimization, accepted 2021-12-10

J. Armesto Barros, A. Mathern*, Recent and future trends of onshore wind turbine foundations*, submitted to IABSE Symposium Prague 2022 - Challenges for Existing and Oncoming Structures, May 25-27, 2022, Prague, Czech Republic (2022)

A. Mathern, J. Magnusson, *Lessons learned from the construction, inspection, and defect assessment of reinforced concrete foundations for wind turbines*, submitted to Applied Sciences.

C. Hamon, M. Persson*, Possible wind farm earnings from frequency regulation markets in Nordic power system*, Cigré Session 2022

External activities

No external activities during this period.