Final report

1.1 Project details

Project title	Future Hydraulic Pitch System for Wind Turbines
Project identification (program abbrev. and file)	64013-0510
Name of the programme which has funded the project	EUDP
Project managing company/institution (name and address)	Hydratech Industries A/S Suensonsvej 14, 8600 Silkeborg
Project partners	Aalborg University
CVR (central business register)	83455128
Date for submission	March 25th, 2020

1.2 Short description of project objective and results

English version:

The project investigated the feasibility of a new pitch system concept where the entire system is moved to the rotating hub and divided in an individual system for each blade. The targets for the concept are; lower cost and higher reliability compared to conventional systems. The project has addressed technical challenges related to a pitch system placed in the hub such as cooling, air bleeding and tank design. A developed rotary testbench has been used to test a prototype of the concept. The project has shown promising results of the functionality of the system including cooling and air bleeding. Furthermore, fault detection and condition monitoring methods related to gas leakage of the accumulators and valve failures has been developed. These methods contribute to an increased total reliability of the system.

Danish version:

Projektet har undersøgt hvorvidt et nyt pitch system koncept placeret i navet med et individuelt system for hver vinge er muligt. Målene for konceptet er en lavere omkostning og en højere pålidelighed sammenlignet med nuværende systemer. Projektet har behandlet nogle af de tekniske udfordringer der er ved at placere pitch systemet i navet, herunder køling, udluftning og tank design. En udviklet roterende testbænk er blevet brugt til at teste en prototype af systemet. Det har vist lovende resultater i forhold til funktionaliteten af systemet, herunder køling og udluftning. Yderligere er der udviklet fejldetektions- og systemovervågningsmetoder relateret til gas lækage fra akkumulatorerne og ventilfejl. Disse metoder er med til at forøge den totale pålidelighed af systemet.

1.3 Executive summary

The project has investigated if a new module-based pitch concept can be feasible. The system consists of three individual modules, one for each blade, all placed in the hub. Each individual system includes a pump and an oil reservoir such that the systems are independent of each other and from a mutual hydraulic power unit placed in the nacelle. By doing this the entire pitch system is placed in the hub and the hydraulic rotary union and the hydraulic power unit is no longer needed. However, placing the entire system in the hub arises some challenges regarding cooling, air bleeding and tank design. In this project these challenges have been addressed by constructing a prototype and testing the functionality of the system. The overall target of the new system is lower cost and increased reliability.

The project has been divided into 4 work packages following the design process. The first work package was to create the first iteration of the design including the rotating tank, cooling and the emergency storage. The focus was to verify that the concept could reach the targets of cost reduction, reliability and functionality. A rough design of a prototype has been built for verification tests which showed promising results. The work package where completed by an internal status meeting at Hydratech Industries, concluding the potential of the new concept.

The second work package dealt with the finalisation of the mechanical and hydraulic design. The control platform where also developed including the selection of hardware. Further attention has been on a well-known issue with hydraulic systems – leakage. This has been addressed by fault detection and condition monitoring of the system. The results of this work have been published in scientific journals through the project in relation to a PhD at Aalborg University. This have further shown the potential of condition monitoring of gas leakage of the accumulator and coil failures of the valves. By implementing fault detection and condition monitoring the reliability of the system can be increased which can lead to a lower cost of energy of the entire turbine. A DFMEA has also been done on the system to examine the reliability of the system, which can be found in the Annex. Work package two where completed by presenting the final concept to potential customers and gaining their approval. Further the construction of a new prototype of the fully functioning system where initialised.

The third work package concerned verification and demonstration of the system. A rotary testbench where constructed for testing the developed prototype under working conditions like the ones experienced in a turbine hub. The focus of the tests has been on the functionality of the prototype to show the feasibility of the technology. The cooling tests showed that the maximum reached oil temperature was 72.4°C which is within the limits of hydraulic oil for wind industry of around 80°C. A temperature of 72°C is though still high and may influence the lifetime in a negative way why there is still room for improvement on this point. An air bleeding concept where also tested. The air bleeding tests showed that the system could remove 82% of the air after 20 minutes. This is assumed to be sufficient as it is expected that all of the air is removed over time. A new tank concept consisting of a floating piston tank was also tested to show that the inlet pressure of the pump was kept within the requirements. It was found that the worst-case tank pressure was 0.7 bar which is within the limits of the pump chosen for this design, the Bucher inner gear pump QX series.

In general, the technology tested in this project has shown some potential. Though the concept needs to be tested in a real wind turbine to completely validate the performance. As for now no turbine OEM's has been willing to test the concept in a test turbine why the project is stopped and finished. The results obtained in the project may still be implemented in some way in new products. This includes the condition monitoring and fault detection methods.

1.4 Project objectives

The objective of the project was to design and develop a new hydraulic pitch system concept for modern wind turbines. The targets of the new system are to have a reduced cost and an increased reliability compared to conventional hydraulic pitch systems. The project was divided into 4 work packages which was the following the design process. This was done to continuously measure if the new developed concept was feasible and to be able to stop the project if it was found that the concept could not reach the stated goals.

The project has been delayed due to changing employees at Hydratech and challenges in filling in the post-doc position at Aalborg university. The PostDoc was changed to a PhD position which was filled be Jesper Liniger.

In the following the objectives and progress for each work package are described.

Initial work:

Before the project was initialised a feasibility study was performed with the goal of ensuring that the concept was designed in the right way. The results were presented to potential customers in order to meet their demands. The feasibility study was done by creating an initial prototype of the system which showed promising performance. The results of the feasibility study where presented to potential customers which responded positively and was interested in the further progress of the project. The first commercial milestone, CM0, was thus completed and the project was started.

Work package 1:

The objectives of WP1 were to create a rough design of the system including the rotating tank, cooling and the emergency storage. The focus was to verify that the concept could reach the targets of cost reduction, reliability and feasibility.

Work package 2:

The objectives of WP2 was to finalise the system design including cooling, mechanical and hydraulic design. The control hardware platform was also selected for the first prototype. The reliability model of the system was also done, hereunder a DFMEA. Also fault detection, monitoring and fault tolerant design and control was examined to increase the reliability of the system. All the objectives were fulfilled including the milestones of the work package.

Work package 3:

The objectives of WP3 was verification and demonstration of the system. This has been done by the construction of a prototype/test setup. Further subsystems such as cooling and the rotating tank must be tested and verified. The verification is done by tests that should verify the functionality of the system (proof-of-concept).

Work package 4:

The objective of work package 4 was to implement the final prototype in a test wind turbine. A requirement for starting work package 4 was that a costumer placed an order on the prototype. This has not been the case why the project is finished after the completion of work package 3.

1.5 Project results and dissemination of results

As stated above the overall objective of the project was to develop and verify a new module based hydraulic pitch system for wind turbines. The verification of the concept has been performed in a rotary test setup to emulate the placement of the system in a wind turbine. The main contributions of the project have been to verify the functionality of the module-based design. Some of the major challenges concerned the tank design, the cooling and the bleeding of air. All these functionalities have been tested on the rotary test bench with success.

The tank concept consisted of a floating piston tank which is simpler and cheaper compared to the bootstrap tank which was proposed earlier in the project. The challenges regarding the floating piston tank is the potential lower tank pressure, i.e. lower inlet pressure for the pump which needs to be within the range of the pump. The tank pressure is dependent on the friction of the piston which has been tested to verify the minimum tank pressure. It was found that the worst-case tank pressure was 0.7 bar which is within the limits of the pump chosen for this design, the Bucher inner gear pump QX series. Further details about the tests and calculations can be found in the annex.

Further, the passive cooling has been tested as the developed system is not equipped with an active cooling system as a conventional hydraulic pitch system. Through tests the thermal time constant of the system has been found which is used to evaluate the thermal performance of the system. Through simulation of design load case data for a 6MW offshore wind turbine the system loss has been found. For the simulations adaptive pressure control has been used in order to reduce the losses and thus the cooling needs. Combining this with the thermal time constant of the system a maximum temperature increase for each DLC can be found. The maximum temperature increase is found to 22.4°C which corresponds to an oil temperature of 72.4°C assuming an ambient temperature of 50°C which is a common temperature requirement in the hub of a turbine. Common maximum temperatures for hydraulic oil for wind industry is around 80°C which is above the found maximum temperature of the developed system. However, to avoid life shortening effects of the hydraulic oil, a rule of thumb is to keep temperature below 60°C. The cooling performance is in general good but further attention may be given to improving the pressure control of the system to reduce the losses even further. Further details about the tests and simulations can be found in the annex.

Another challenge of the hydraulic pitch system placed in the hub is the removal of air in the system. Different technologies for bleeding the air has been tested throughout the project. A solution consisting of an air sensor and a control valve has been selected as this solution has shown the most promising results. Tests on the rotary test bench where air has been led into the system and then bleeded has been carried out to validate the functionality of the solution. These tests have shown that 64% of the air that was added to the system is removed after 10 minutes. After 20 minutes 82% of the air was removed. The functionality of the air bleeding system has thus been verified. However, the system needs to be further validated in a real wind turbine to show the real performance of the air bleeding system. Further details about the tests can be found in the annex.

Throughout the project the results have been presented to potential customers who in general have shown great interest in the project. The results have mainly been presented at meetings as a part of completing the milestones.

In addition to the functionality validation of the new developed pitch system a lot of effort has been given to the reliability of the system. Most of this work has been done by Jesper Liniger who has been a PhD student in this project. His work concerns methods for design and reliability evaluation of fluid power system along with reliability-based design of fluid power pitch systems. Also, several condition monitoring methods have been developed including gas leakage in accumulators and solenoid faults which has been identified as some of the most important components regarding the reliability of the system.

The results of his work have been published in journals and presented at international conferences. A list of these are given below:

1. **Reliable Fluid Power Pitch Systems – A Review of State of the Art for Design and Reliability Evaluation of Fluid Power Systems**
   - Conference: ASME/BATH 2015 Fluid Power and Motion Control

2. **Reliability Based Design of Fluid Power Pitch Systems for Wind Turbines**
   - Journal: Wind Energy, http://onlinelibrary.wiley.com/journal/10.1002/(ISSN)1099-1824

3. **Feasibility Study of a Simulation Driven Approach for Estimating Reliability of Wind Turbine Fluid Power Pitch Systems**
   - Conference: Proceedings of European Safety and Reliability Conference 2018 (ESREL)

4. **Reliability Based Comparative Study of Fluid Power Pitch Systems for Wind Turbines**
   - Conference: ASME/BATH 2017 Fluid Power and Motion Control

5. **Signal-based Gas Leakage Detection for Fluid Power Accumulators in Wind Turbines**
   - Journal: Energies

6. **Model-based Estimation of Gas Leakage for Fluid Power Accumulators in Wind Turbines**
   - Conference: ASME/BATH 2017 Fluid Power and Motion Control

7. **Early Detection of Coil Failure in Solenoid Valves**
   - Journal: IEEE/ASME Transactions on Mechatronics

1.6 Utilization of project results

As no commercial partner for implementing the final prototype in a test wind turbine has been found, the new pitch concept has not been used commercially. If a partner is found in the future the results originating from the project can further developed and the concept can be commercialised. However, the results have contributed to the general development of pitch systems as new technology has been tested and verified which will be needed for a hub mounted pitch system.

The work done on reliability and condition monitoring has resulted in a new industrial PhD position within reliability and condition monitoring of fluid power pitch systems. The new PhD project is based on many of the results in this project and is expected to contribute to further development within this field. This should also be seen as a part of an increased focus towards condition monitoring and fault detection from Hydratech industries and a step in implementing the results of the current project in future pitch system. It is expected that the developed condition monitoring methods can be implemented in future systems as an attempt of improving the reliability of the system. Furthermore, it will be used to market Hydratech as a leader in fluid power pitch systems and be used as one of the selling arguments for selecting Hydratech as pitch system provider when taking/negotiating with new and existing customers.

The results have also been used for dissemination activities during the PhD student which was a part of the project. A list of these activities can be found in section 1.5.

The results may also contribute to realize the energy policy objectives as the results may lead to more reliable pitch systems. By increasing the reliability, the total cost of energy for wind turbines may be decreased, which will increase the competitiveness of wind energy in general. This will also contribute to the vision of increasing the part of Danish electricity coming from renewable energy sources.

1.7 Project conclusion and perspective

The project dealt with the development of a new pitch concept where the entire system is modularised and placed in the hub such that there is a system for each blade of the wind turbine. The results have shown that the concept is feasible and have great potential in terms of increased reliability and decreased cost. Some of the challenges of moving the entire pitch system into the rotating hub was related to passive cooling, tank design and bleeding of entrapped air. Through test it was shown that that the passive cooling of the system was sufficient in terms of fulfilling the temperature requirements of the oil. Better cooling performance could be achieved by better pressure control which may be a future research topic. The tank design was also found feasible as the minimum tank pressure were within the limits of the chosen pump’s inlet pressure limits. Furthermore, the piston movement pattern of the tank is, based on simulations, found healthy as the piston movements in general is above 7mm which is a design rule of thumb for standard seals. The design has also been validated by experienced system designers at Hydratech Industries. Test has also proved the air bleeding technology for the system using an air sensor and a control valve. In a rotary test setup, it has been shown that 64% of the air can be removed in 10 min of normal operation. As the air leaked into the system is assumed to come from the accumulators and occur very slowly over time the air bleeding performance is found sufficient.

The project has also produced condition monitoring methods for detecting gas leakage in the accumulators and solenoid failures in the valves of the system. The methods have been validated by tests and simulation and is published in journals and conference proceedings. It is expected that the developed methods can be implemented in future systems. The results are also an enabler of the future technology development within condition monitoring which will become an increasing focus area at Hydratech Industries.

To sum up, the project has shown great potential for a new developed pitch concept and validated the feasibility of the concept. To take the project to the next level a commercial partner who is willing to test the system in a test turbine needs be found. This has not yet been possible therefore the project is completed without the last work package. However, the results of the project can be implemented in the future if a willing wind turbine OEM is found.

Annex

The annex consists of the following documents:

- PhD thesis including published papers
- Prototype report
- DFMEA