Final report

1.1 Project details

Project title	Development of repair method for damaged yaw rings in windturbines (Udvikling af krøjekransproteser som servicevirkemiddel for slidskadede vindmøller)
Project identification (program abbrev. and file)	Journal no. 64016-0088
Name of the programme which has funded the project	EUDP – Energiteknologisk Udviklings- og Demonstrationsprogram.
Project managing company/institution (name and address)	A/S Grenaa Motorfabrik 1-5 Sdr. Kajgade 8500 Grenaa, Denmark
Project partners	S.E. Blue Renewables
CVR (central business register)	40568611
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1.2 Short description of project objective and results

The wind turbine industry has seen a rapid growth over the past 30 years. This growth has been in the population of windturbines as well as in the amount of turbine designs where the power output of the individual turbine unit has grown from about 50 kW and now up to around 10.000 kW for the largest turbines.

During this rapid development of the industry a number of standard service concepts has been formed to deal with different operational problems / damages. These repair concepts are mainly based upon a “module replacement idea” where a damage to a component is rectified by replacing the entire component. While this works well and feasible for smaller components like electronic modules or hydraulic pumps etc. then it is a very expensive approach in the case of main component damage.

The demand for cheaper green energy has led to a need for cost saving repair methods and ideas for on-site repair methods for main components are developed in these years.

This project addresses a low-cost repair concept for one of the most costly repair actions a turbine owner may encounter: Damages to the yaw ring gear. Due to various conditions a yaw ring (the main geared ring which is the central part in a turbines ability to “turn the head into the wind”) may suffer damages to its gear teeth. Today’s standard repair solution is to dismount the entire rotor and the nacelle and take it to the ground for installing a new yaw ring. With the massive crane costs and engineering costs this operation amounts to several hundred thousand Euros for a mid to large type of turbine.

It has been the objective of this project to develop an on-site repair solution which allows repair without assistance of crane and without major dismantling of the turbine. turning main components in the turbine.

During the project we have developed a type of machine which can mill the damaged section of a damaged yaw ring away and leave a well-defined pocket with narrow tolerances in which a repair section can be installed. The project has also focused upon developing a type of machining equipment which is simple to install and simple to use during the machining operation in the turbine.

Further, the project has also resulted in developing a way to manufacture these repair sections in a flexible way which can be performed in a machine factory without special gear milling machines which are very rare and expensive for this size of ring gear parts.

1.2 Kort beskrivelse af projektmål og resultater

Vindmølleindustrien har oplevet en hurtig vækst gennem de seneste 30 år. Denne vækst har været i antallet af vindmøller såvel som i mængden af vindmølledesigns, hvor den enkelte turbineenheds effekt er vokset fra ca. 50 kW og op til omkring 10.000 kW for de største vindmøller.

Under denne hurtige udvikling i branchen er der opstået et antal standard servicekoncepter til at håndtere forskellige operationelle problemer / skader. Disse reparationskoncepter er hovedsageligt baseret på en "moduludskiftnings-ide", hvor en skade på en komponent afhjælpes ved at erstatte hele komponenten. Dette virker godt og er fornuftigt for mindre komponenter som elektroniske moduler eller hydrauliske pumper mv., men det er en meget dyr løsning i tilfælde af skade på en hovedkomponent.

Efterspørgslen efter billigere grøn energi har ført til et behov for omkostningsbesparende reparationsmetoder, og der bliver derfor udviklet ideer til on-site reparationsmetoder på hovedkomponenter.

Dette projekt omhandler et billigt reparationskoncept for en af de dyreste reparationer, som en vindmølleejer kan komme ud for: Skader på krøjekransen. På grund af forskellige forhold kan en krøjekrans (gear-ringen, som er den centrale del i en vindmølles evne til at "dreje toppen – nacellen - ind i vinden") få skader på tandhjulstænderne.

Dagens standard reparationsløsning, når der opstår sådan en skade, er at afmontere hele rotoren og nacellen og hejse den ned på jorden for at installere en ny krøjekrans. Enorme kranomkostninger og montøromkostninger gør, at sådan en reparation beløber sig til adskillige hundrede tusinde euro for en mellemstor vindmølle .

Det har været målet med dette projekt at udvikle en on-site reparationsløsning, der muliggør reparation uden hjælp af kran og uden større demontering af turbinen.

Under projektforløbet har vi udviklet en type maskine, der kan fræse den beskadigede del af en skadet krøjekrans væk og efterlade en "veldefineret lomme" med snævre tolerancer, hvor en reparationssektion kan installeres.

Projektet har også haft fokus på at udvikle en type bearbejdningsudstyr, som er let at installere og simpelt at anvende under bearbejdning i vindmøllen.

Desuden har projektet resulteret i udviklingen af en metode til at fremstille disse reparationssegmenter på en fleksibel måde, som kan udføres på en maskinfabrik uden specielle gearfræsemaskiner, der er meget sjældne og dyre for denne størrelse af tandhjulsdele.

1.3 Project objectives

It has been the objective of this project to meet market demand for smart-repair-solutions and thereby to lower the overall operational costs of wind turbines.

The yaw system and especially the yaw ring is a very expensive component to replace and the objective of this project was to develop a repair method which enables on-site repair of a damaged yaw ring.

Crane costs and down-time costs (mainly during waiting for cranes which are a bottleneck resource in the entire wind industry), which are in effect not value adding, constitutes by far the largest part of costs involved in the traditional component exchange method. This project has the objective to minimize non-value adding costs of the repair and leave a technically functional result which can be achieved at a fraction of the traditional repair costs.

Due to the wide span of different turbine models with each their specific design, it has also been an objective to design a type of machining equipment which is flexible and relatively simple to adapt from one turbine model to another.

Finally, the manufacture of repair sections for yaw rings has been a type of manufacture which would normally be performed by specialized gearwheel factories and only a few of these factories have machinery large enough to manufacture these parts. This drives up the price and delivery time for these repair segments and traditional manufacturing of the repair sections would thereby be a major obstacle for the flexibility which is paramount for a repair solution.

Therefore we have followed an approach of simplifying manufacture of low production volume segments which can allow a machine factory as Grenaa Motorfabrik to manufacture parts on short lead time and without investing in potentially enormous inventory in order to have a suitable portfolio of repair segments.

The project has showed the way to further develop the equipment and methods for machining as well as providing the required spare parts (segments) and tooling in an inexpensive way.

It is our target and belief that the project will create the basis for a cost-reducing repair technology which will benefit the wind turbine operators and furnish Grenaa Motorfabrik an extra component in its repair portfolio which will make good future business for the company as well as large savings for our windturbine clients.

1.4 Project results and dissemination of results

<u>The machine and process design</u>

The project started out with a period of generating ideas for possible ways to obtain the above mentioned objectives. Especially the focus was on which type of machinery could perform a precision machining operation under site conditions with limited space and limited access openings to enter into the space where the yaw ring is situated.

A couple of different turbine designs were studied in order to get a general idea of how to design a machine which would be universally adaptable, that is, a machine which will be versatile and adaptable to different windturbine models without starting from scratch for every turbine design.

It became clear that CNC-machinery (computer controlled movements of the machine used to describe the contour of the milling process) would become very complex and vulnerable in a cold and harsh on-site environment. And worst of all, this type of machinery cannot be repaired by any windturbine technician because of its electronic complexity.

After a number of potential methods were examined and discussed we decided that the following factors were very important for the success of the project:

- Flexibility and adaptability of the machinery so that it can relatively easily be adapted from one windturbine model to another
- Simple and sturdy machinery which can be repaired by any qualified mechanic or electrician in case of problems during the use. These same qualifications are always in place in a windturbine technician environment.
- Precision in the way that on-site machining tolerances as in a factory environment can be achieved.

All the above mentioned requirements led us to focus on a machine which would be mountable onto the wind turbine by simply removing one of the yaw gears and installing the machine in its place.

The challenge was then naturally to make a compact design as space is limited inside the size of a yaw gear drive and still to obtain the required free movement of the machine axis which we needed.

After realising the design path to follow, we initiated an intensive design work and manufacture of a number of parts and prototype machinery which allowed us to perform partial tests and move on to the next stage of design once each component of the machine had been tested under simulated operation in the factory.

After a long period of design-manufacture-test-scrap and then improve and build increasingly better machinery we decided to take the machine to site-test. By then we had the basic machine developed and tested in a workshop environment as good as it could be done and field testing was the next step.

Before that could be done we had to design the repair sections for the yaw drive which turned out to be a little challenge in itself.

<u>Yaw ring repair segments</u>
The traditional manufacturing technique of gears and geared rings is that the ring is turned and drilled and then placed on a gear hobbing machine where the teeth are hobbed (milled). These rings are very large and only a few gearwheel factories in Europe has this size of machine. The few factories with these machines are generally busy with machining large series of new parts and they are generally not interested in machining small batch production which is what was required by us.

To buy a new ring from the turbine manufacturer would in theory be a possibility. However, it would be an unsure way of making a service concept because the availability of such rings from the turbine OEM is questionable. From experience we know that parts availability is varying depending on the business focus of management. Further, we did not wish to have the OEM's hold our fate by a concept where we would be depending on their mood for supply of a service which would essentially be in competition with their own repair solutions (selling and installing complete yaw rings).

In case we were to use complete rings for manufacturing segments this would require that a section is machined or cut out of a ring. This has another problematic factor. All heat treated and machined components have internal stresses. The balance of these stresses allows the part to keep its form. Once a section is taken out of a gear ring, these stresses will be released and the part will change its geometry. Therefore, a section of a complete ring would not meet our requirements to be a precise part.

For the above mentioned commercial and technical reasons we decided to find a way to manufacture the repair sections flexibly and without depending on Windturbine OEM's. Further we needed to develop a way which would allow us to manufacture these segments without having to depend on the few gearwheel manufacturers which can manufacture yaw rings. In short we needed an approach which would enable us to manufacture precise segments – not to manufacture complete rings. Thereby we would be able to meet the following objectives of all successful repair concepts:

- High flexibility in adapting methods to different windturbine models
- Quick response in manufacturing the required parts upon client order
- Low inventory of different parts (if the repair method is to be used in a large number of turbine models it would require huge investment in parts in the case that they should be stocked instead of being manufactured when needed)

With these objectives in mind we realised that we needed a manufacturing process which we could perform in-house in our own machine factory.

We developed a type of tooling and fixture which we could add to a large milling machine and we would thereby be able to machine the segments tooth-by-tooth and at the same time to test the result of the machining process in a similar way to how a complete ring gear is tested. The challenge here is that base-tangent measurement of the teeth need to be measured for obtaining the required accuracy. However this measurement is performed over a large number of teeth e.g. 24 teeth in a larger ring gear – and if a repair segment has only 7-10 teeth it is by normal methods naturally not possible to check this dimension.

We designed the method and tooling for this manufacture and thereby we have reduced delivery time for segments from being several months down to weeks (for new designs) or even days for existing designs.

<u>On-site test of the machinery and repair concept</u>

During installation in the turbine a number of challenges were encountered. One was that the movement of the vertical axis of the machine was more power demanding than expected in cold weather conditions. This led to a note to improve the design at a later stage. The machine was operational however slower in the movement upwards than expected and targeted.

More problematic was another factor which was somewhat of a surprise to us. The turbine would have to perform yaw movements with the machinery installed. However it turned out that the bearing-guiding system in the turbine which keeps the nacelle in position over the centres of the tower and of the nacelle flange were very poor and resulting in that the nacelle moved several millimetres when yawing motion was shifted from one direction to another. As this made it practically impossible to operate with the machinery which we had spent a long time and much costs it was a serious problem for the entire machining concept which we had developed. In order to perform a milling operation with narrow tolerances it is required to have a dependable centre reference as well as well-defined movements of the nacelle.

We spent some time after this in further trouble shooting and idea generation. We concluded that the machinery was a good and suitable design for the type of machining operation and it met the initial basic design criteria for the machine which we had defined. During this evaluation it also became clear that any other design which we could imagine would be a departure from our decision not to design a CNC-machine. Since the CNC-machine would have a number of operational weaknesses which would cost time and money during performing on-site jobs, we kept our basic design idea of a relatively simple electro-mechanical design which is robust and easy to repair by normal windtech-personnel, in case it would suffer problems during operation. We would therefore not go back and start the design process all over and come up with a different machine design.

However, it was clear that in order to overcome the problems the challenge would be either to make the machine tolerate the uneven and imprecise nacelle movement or we would have to find a way to guide the movement of the nacelle so the movement of it could be performed well defined and with precision.

Having realised this, we focussed upon this task and developed an adjustable set of slide bearings which were installed in the turbine during the repair process. We also worked out a way of adjusting the correct centre-axis of the nacelle so that the yaw-ring machining would be performed with the correct centre-reference. This factor is of importance to the long term reliability of the repair work since inaccuracy would lead to false gear meshing and reduced service life. These adjustable slide bearings were manufactured and after installing them in the turbine we managed to adjust the axis of movement and to control the path of the nacelle within about a tenth of millimetres accuracy. After manufacturing these additional components and installing them in the turbine, we could start the machining process. The basic machining process went relatively smooth and the first repair segment was installed. It fitted perfectly – it was concluded that the machine basic design as well as the special measuring equipment which we had designed for testing the fit of the segments was a precise way of doing this, since the dimensions fitted within normal workshop tolerances of a few hundreds of a millimetre. The machine and tooling had proved its precision although it was still to be improved in terms of speed.

The imprecision of the nacelle movement has another problematic component as this causes the centre distance of the gear mesh between yaw-gear-gearwheels and the yaw ring to shift by millimetres. In gear design the centre distance is laid out with small tolerance and a large variation in the centre distance as was found in the turbine would have been a major contributing factor in the problem generating – it may be the actual cause of the tooth damage to the yaw ring. The turbine owner was made aware of this and advised to have the guiding system overhauled for better precision.

Another component of the machining was the drilling process. It was a secondary process which we had assumed would be uncomplicated. We had devised a primitive stand for an angle drilling machine but it turned out to be unsuited for the job. The drilling was performed more or less "per hand" and the result was technically satisfactory but it was clear that a proper solution for this task was to be developed.

After the on-site test the equipment was taken back to Grenaa Motorfabrik for design improvements.

The operational challenges experienced by the on-site engineers were evaluated by the design team in dialogue with the engineers. The machine design was reworked and the new design was debated in the design team and with the engineers. A new reworked machine was manufactured where essentially the vertical drive system was reinforced and a more powerful motor controller was built for that purpose.

Further, the machine was extensively redesigned so that it could perform the secondary operation of drilling the radial holes which were required as part of the fastening of the new repair segments. One extra moving axis of the machine was added to the design and the axial spindle bearing arrangement was redesigned in order to enable it to absorb the larger axial forces which would arise from the drilling operation.

After the redesign, the machine was rebuilt and tested in the workshop. The vertical movement showed the expected improvement in power and speed and the drilling operation was also tested and found to work satisfactorily.

1.5 Utilization of project results

During all phases of the project we have been in continued contact with potentially interested parties in the project results.

Initially, we performed business trips in Denmark, Germany and Sweden in order to gather information about the types of turbines where the ring gear problems exist more typically. During these trips we were in contact with clients operating thousands of turbines of many different types and models.

We selected a few turbine models to be our first and subsequent targets for the development process.

During the same interviews we also received the information of another field of potential application which has a similar repair potential. For business reasons we do not wish to disclose this possible future spin-off in this report.

Later in the project we have participated in international exhibitions in Husum (Husumwind 2017) and in Hamburg (Windmesse Hamburg 2018) where we have promoted the new business area and where we have been in contact with a very large number of potential clients.

Outside Europe we have visited Canada where we have had meetings with 2 strategic partners for Canadian repair work on turbines. Canada is a relatively new windturbine country which means that the industry has already matured when Canada entered into wind power. Compared to Europe the Canadian population of turbines is a very tidy population with hundreds or even thousands of identical machines. Therefore a concept of repairs for these machines is important to us since this can be realised with few model variants and on a larger number of identical machines than is the case in Europe where the population is much broader and more complex in terms of different turbine models.
Meetings were held in the Ontario region where most of the Canadian industry is concentrated. The meetings included discussions with a company which can perform the actual jobs in a cooperation as well as with a potential representative company where the manager has contact to practically all wind turbine owners in Canada after more than 20 years of wind turbine experience at different levels.

We have focussed on distributing the news of the project and the repair concept on a face-to-face basis where we have met clients at their offices and on the 2 above mentioned exhibitions. Our targeted clients are large owners of wind farms and our experience in sales and promotion with these companies is that the most effective way to get orders is to dig into the organisations and find the key persons and then work persistently on promotion our concepts. This same approach has been applied in this project and the concept has been made known to a large base of potential future clients.

1.6 Project conclusion and perspective

We have performed a development project which has met all the objectives set out from the beginning.

During the project we met a number of challenges but all were overcome and we managed to end up with a strong repair concept which we will promote and pursue in our future business.

We expect this concept to add engineers to our on-site teams over the next years and to reach a doubling of our on-site activities within the next 3-4 years.

Further, we have found another possible spin-off area of application which we will investigate further in the future.

The windturbine industry will benefit from this project which adds to other new developments of service concepts aimed to make green energy operations cheaper and thus more competitive with fissile fuelled energy sources.