EUDP-Final report

1. Project details

Project title	Global Team Turbine
Project identification (program abbrev. and file)	Journalnr.: 64013-0148
Name of the programme which has funded the project	EUDP 13-I
Project managing company/institution (name and address)	Vestas Wind System A/S Hedeager 42 8200 Aarhus N
Project partners	Gates Corporation, USA RWTH Aachen University, Germany
CVR (central business register)	Vestas Wind System A/S: 10403782
Date for submission	2013-03-06

2. Contents

3. Short description of project objective and results

The objective of the Consortium was to design, build and test a cost efficient and reliable wind turbine nacelle utilizing a beltdrive instead of a traditional gearbox. Vestas and the project partners, together designed and build a series of tests in order to identify the capabilities of such a concept. The objective was to identify the best concept configuration with the aim of verifying the technology in a true wind turbine prototype.

After having designed and tested two configurations, a final and full size demonstrator of a belt drive transmission was made. The full size demonstrator concluded the project by demonstrating the potential and capabilities of utilizing a beltdrive instead of a traditional gearbox, which in most cases showed positive and promising results.

Konsortiets mål var at designe, bygge og teste en omkostningseffektiv og pålidelig vindmølle nacelle som anvender bælte-drev i stedet for en traditionel gearkasse. Vestas og projektets samarbejdspartnere designede og byggede sammen en række tests, for derigennem at identificere conceptets potentiale. Formålet var at at identificere den bedste conceptconfiguration med det mål at verificere teknologien i en komplet vindmølle prototype.

Efter at have designet og testet to konfigurationer, blev der lavet en fuldskala bæltedrevs-test. Denne test var dermed den afsluttende del af projektet, hvor conceptet potentiale og evner som transmission i en vindmølle blev eftervist. I de fleste tilfælde viste conceptet positive og lovende resultater.

4. Executive summary

Generally the revised project plan has been executed as planned. In the end, however, the project completion date was postponed by 3 months. Primarily due to preparation of the final demonstration rig, taking longer than planned.

The effort by all partners has been strong and the commitment high. The total actual project hours delivered, is twofold compared to the planned total project hours.

The EUDP funding has derived from the Consortiums own private funding in combination with the EUDP grant, which has been decisive in order for the project to be viable. Each participant has contributed with in-kind and cash financing, the largest proportion from Vestas who has administrated requirements, engineering and test activities.
Gates provided belts, sized belts to meet requirements, provided on site belt drive design and system testing consultation, and evaluated many concepts using simulation and other design tools.
The project was split in 5 main activities and 3 demonstrations have been performed. A down scaled proof of concept demonstration was designed, build and tested. The main purpose was to get quick input on conceptual system and integration design options, but also to get initial indications on transmission efficiency, noise & vibration levels and various functional elements. Later more thorough technical design requirement validations were done in separate demonstration, at the Aachen University with help of the IME Aachen GmbH. Finally a full size demonstration of a partly designed and build wind turbine nacelle was undergoing severe tests. This demonstrator will continue running tests, also after completion of the EUDP funded project.

The overall project results are positive and the potential of using belt driven transmission in the Wind industry remain high.

5. Project objectives

The primary objective for the Global Team Turbine project is to design, build and test a wind turbine nacelle utilizing belts instead of a traditional gearbox or direct drive for the transmission of mechanical energy from rotor to generator in a wind turbine.

There is always an element of risk when introducing new technology to established markets, but the key elements of the technology: low cost and system simplicity provides opportunities to new and emerging markets where there is a need for low cost turbines with high reliability and low operations & maintenance cost.

In partnership with the world largest timing belt manufacture, Gates Corporation, and the leading university for wind power drives, RWTH Aachen University, Vestas Wind System A/S has facilitated and project managed the exploitation of timing belt transmissions for wind turbines.

The project application reflects the learnings and assumptions of March 2013, where belt drives for wind was set to Technology Readiness Level (TRL) 3 with the opportunity of lifting this to level 6, within the 18 month project duration. In April 1st 2015, when the project was officially kicked off, much more learnings had come through. TRL was now estimated to 1.5, and consequently a different approach was defined and approved by EUDP. The target was still to reach TRL 6, which is a concept demonstration. Reaching TRL 6, has been accomplished.

The project application was sent to EUDP on March 3rd 2013, but the project kick-off was postponed to April 1st 2015. The time in-between was used to redefine the consortium set up, as the EUDP project approval required that Vestas Wind System A/S should be the project manager. Afterwards the original applicant, Norwegian company FoGear, a subsidy to Fred Olsen AS, decided to step out of the Global Team Turbine project. During that same period, also Hydro ASA, which was thought to be the developer of aluminum sprockets and pulleys for the belt transmission, decided to retire from the project even before the project had started. Reason being that the new learning and reduced TRL level, clearly favored steel sprocket due to the better material capabilities. Aluminum is however still interesting, but is today, still seen as a more complex and future optimization opportunity of belt transmission system cost and weight.

These consortium and project activity changes, was judged not to impact the timeline nor the final deliverables. Later the project's final completion date had to be postponed. But for other reasons, described further below. The project activity and consortium changes, did however, impact the workload and packages of the remaining consortium partners. Vestas Wind System took on all the majority of the original planned FoGear effort, and Vestas designed the sprockets based on general industrial recommendations provided by Gates. Also additional 2000 hours was transferred to Aachen University, for additional Multi Body Simulations.

A project plan reflecting the above described changes is to be found in Annex **Fejl! Henvisningskilde ikke fundet.** of this Final Report.

The project approach was split in 5 main activities. Some of these had been executed simultaneously. Below is a short description of each work package:

5.1 WP1 Turbine integration

Global Team Turbine function requirement specification. Focus on the belt gear system and the gear system interface with the nacelle. Requirements to interfacing subsystems as cooling, brakes, rotor lock and eventual lubricant system was investigated in this phase. The objective was to re-use as many components as possible from standard designs in order to save costs.

5.2 WP2+3 Validation of power split/recombination and stiffness

After many fruitful initial meetings and workshops between the partners, and in particular from thorough kinematic analysis, performed by Valcon Consulting A/S, on potential nacelle concepts including a belt drive, it became clear, that the deployment of belt drives in wind, results in belt drive requirements, not previously seen. Especially structure stiffness impact on belt drive performance is crucial basic knowledge. The project did set up models to calculate stiffness impact. These were validated on full scale demonstrator tests at the Aachen University. The tests were performed by IME Aachen GmbH. Design sketches can be found in the Annex 9.2

5.3 WP 4 Concept demonstration

Beside the learnings from WP2+3, further investigation was done on different belt drive designs. The most promising ones had been built up on a scaled back-to-back test rig set up. Design sketches can be found in the Annex 9.3. The back-to-back rig was designed and build by Vestas with support from the partners. The purpose was to simulate and demonstrate the two most promising wind turbine integration concepts. Focusing on the main uncertainties identified:

- Power recombination on the second stage of the transmission
- Belts run off pulley
- Power load distribution
- Tooth jump on main pulley
- Thermal impact (carbon belt & steel pulleys)
- Noise
- Efficiency

5.4 WP5 Nacelle design and built

Having obtained a lot of knowledge from WP1-5, it was now possible to unify the learnings into a design. This would naturally have to be a design suitable for a wind turbine, which is why a conceptualization process for the nacelle for this final project demonstration was carried out. Design sketches of the final design is to be found in the Annex 9.4.

Manufacturing of most components was relatively uncomplicated. Other components like the machining of the large main pulley and the tight tolerances needed for test purposed, appeared difficult. Niebuhr Gears A/S and IPL A/S has put in considerable effort to make this possible.

5.5 WP6 Nacelle testing

Originally the test facilities at either Aachen University or Vestas, was planned to be used for the primary demonstration. However, Aachen test facilities were occupied for the time specified. Thus, it was decided to move the test activities to DTU Risoe, giving the additional opportunity that would have allowed for continued and more intensive test activities, also after the completion of the EUDP project. The test rig at DTU was however incomplete, and the effort to complete this rig appeared much more complicated than initially judged. As a consequence of this unsuccessful test rig work, the project plan slipped by 3 month, and it is the direct root cause leading the postponement of the project completion date.

The test was instead moved to Vestas own facilities, where an endurance test will be performed and continue, also after completion of the Global Team Turbine project, using this nacelle and test rig.

The foreseen technical risk has been evaluated and quantified. Main technical risks:

- Technical risk related to lifetime, efficiency and system performance
- Finding the best solution for the belt drive train integration into the complete system of a nacelle

No severe additional technical risks has been identified.

The test itself consist of following steps

- Basic concept functionality
- Extended concept functionality
- Concept performance and efficiency
- Durability/lifetime
- Extreme torque
- Electrical configurations

Commercial risk for future integration and deployment of the demonstrated technology in Wind are:

- Market penetration of this alternative technology
- Size of wind turbine product including belt drives and the supply chain capabilities, in the chosen market segment for product launch.

6. Project results and dissemination of results

The overall project result is positive. Belt transmission for wind turbines is still perceived an innovative technology with high potential to provide an enhanced solution in comparison to conventional gearbox solutions as it includes a simplified design that reduce the complexity, lowering the overall component costs. It also includes fewer components and subsystems, and may ultimately reduce the overall cost of energy significantly. Naturally also traditional transmissions wind turbines are improved on efficiency, cost and component lifetime. On the other hand, the design of belt driven wind turbines is still immature and the opportunities for optimizations are many. Reducing the total nacelle weight by even smarter integration design and lighter materials, that traditional geared wind turbines would not allow for, may be the primary future LCoE reduction driver.

Learning and results of each work package:

6.1 WP1 Turbine integration

This was the classic “forming and norming” period of the consortium project. Participants were to get to know each other at both personal and functional levels. E.g. we were late in realizing that “robustness” means one thing by Gates and another thing by Vestas. There were not major issues, but combined with a range of other minor confusions, the building of a common language and engineering process, was an unexpected learning period. Through high focus on the importance of collaboration and constantly taking time for thorough explanations and intense listening, we never got into a storming period of the project. Throughout the project execution, periods have been tense and very busy, but the activities were always carried out in a respectful, focused and efficient manner.

Several consortium workshops were executed. Attention to the learnings from the concept demonstration performed previously in another project were given.

Main focus of this work package was to define system integration concepts. Many concepts were analytically validated, but no clear answers were given. Afterwards high focus was put on the system level requirements for belt drives in Wind. The output of this exercise was a list of technical uncertainties generic to most of the defined system level integration concepts. Consequently, this pushed for deep dive analyses in WP 2 + 3, and the system integration concept decision was postponed to WP 5, which allowed also to harvest the concept demonstration learning results of WP4 beforehand.

6.2 WP2 Power split and stiffness requirements validations (stage 1)

A kinematic analysis lead to a defined need of validating the requirements for stiffness and tolerances of the transmission. In order to do so, it was identified that a MBS (Multi body simulation) would be the best approach to understand this and test different designs and configurations. This means that it was necessary to identify the properties of the main belt. As a part of this, the following areas were investigated:

- Modal analysis
- Kinematic gear ratio
- Torsional stiffness and damping
- Natural Frequencies
- Sensitivity of Misalignment and Eccentricities
- Impact of Pretension levels
- Tooth jump
- Tracking
- One side failure

For the investigation, a belt drive concept demonstrator was designed. The main focus here was to proof the power split and validate the mentioned properties of full scale high-torque belts. The belt drive demonstrator was assembled and tested at the IME Test Center (ITC) of the university in Aachen. The test period at ITC was managed to be 12 weeks from mid-October to beginning of January 2016.
Further purpose of the test was, to validate the results of the finite element (FE) simulation models and the multi-body-simulations (MBS). The validation has been performed successfully and the validated mbs model could be used to get a deeper understanding on drivers that have impact on belt drive system behavior.

A lot of learnings were made. Some concerns were eliminated and new also emerged. These learnings have since composed the basis for the MBS and understanding of the capabilities and limitations of the system.

6.3 WP3 Power recombination and stiffness requirements validations (stage 2)

After the successful testing of the first stage the second stage of the belt drive was added to the Belt Gearbox (WP3). The test period for testing was from mid of March 2016 to the beginning of May 2016. The main focus of WP3 was to learn the fundamentals about different design concepts of the belt drive system. The first design was without load recombination. The second design was with load recombination on the second stage. And the third design had a differential on the second stage to recombine the load. The torque fluctuation, load split and efficiency for all three concepts were evaluated. Those results helped to choose the most robust design. Additionally the results were used to validate the mbs model.
The main areas that were investigated was:

- Modal analysis
- Power balance
- Power recombination
- Pretension
- Belt strain
- Efficiency

The test showed that our concerns regarding recombination was, unfortunately, viable. It was however clear that by having an advanced pulley design, and with a casted belt (not a prototype) the issues would be reduced potentially making the principal applicable. However, the two different designs didn't show any significant difference in decreasing the issues, which is why a new transmission design was made for WP5 + WP6. The new design would completely obviate a mechanical recombination, by implementing two generators and thereby make the recombination electrically.

WP2 + WP3 has together constituted the physical validation of the multi body simulations of the belt drive transmission which has been, and will be the tool for future designs of belt drives nacelles.

6.4 WP 4 Concept Demonstration

Through functional demonstrations and subsequent evaluations, the basic features and operational design requirements of a belt drive, have been identified.

For WP4 the purpose was to investigate the concept of having a two or a three split configuration on the 2nd stage. The reason for doing so was because of the potential cost savings on belts, as a two split would result in half the torque and thereby only require half the width of the belt, and likewise for a three split meaning approximately 1/3 of the belt width.

We experienced that three split leads to tooth jump on the main pulley by full load. This clearly indicated that the wrapping angle would have to be increased. Technical solutions like idlers to avoid tooth jump, was present, but this introduced a decrease of transmission efficiency. For the concept with 2 split, the same issues was not met. Consequently the continued system design was chosen to be a 2 split configuration.

Areas that were also investigated:

- Tracking
  - On WP2 and WP3 high tracking forces had been identified. This was not the case for WP4, indicating that the tracking is, aside from alignment, related to the belt width.
- Power load distribution
  - This was not a problem
- Thermal impact
  - It was identified that the sprockets heat up under operation. This means that the thermal impact must be considered. As the carbon reinforced belt have a negative expansion coefficient, it will not expand equally with the steel structure. This issue was quantified and high valuable learnings for the following demonstrator design was identified.
- Noise and vibration
  - Noise and vibration tests and measurements were performed. Both noise and vibration results were higher than what is normally seen in similar tests on traditional gearboxes. Consequently additional tests for noise and vibrations were pushed to WP 2-3
- Efficiency
  - The transmission efficiency results were in most running time constantly above 90 %

Additionally: Valuable learnings on generic belt transmission system anatomy emerged during the design and demonstration of the back-to-back rig. Among other minor issues, we experienced that pretention settings of belts is difficult and needs a clearly defined process integrated in the system design.

Problem: During demonstration of this rig, pulley shaft bearings often heated up. Several attempts to identify the root cause and overcome the issue was made. Minor shaft misalignments were finally identified as root cause. The system design did not allow for solving the issue, so most demonstration and test were executed with this controlled failure. System design inputs on how to fix shaft alignment was handed to design of demonstrators in WP 2, 3 and 5

6.5 WP 5 Nacelle design and build

The process of the nacelle design has been a long and ongoing process, as new learnings had kept coming in. The obvious step was to do an enhancement of the back to back test as many considerations had already been made back then. By implementing the learnings from WP 2 and 3, it was possible to optimize the design by the use of Finite Element Analysis. By doing so, the concept has been designed with requirements to stiffness rather than strength, which is essential in order to obtain a good lifetime for the belts. A part of this process also identified the need for a thermal compensation system, due to the thermal expansion of the transmission. Due to time limitations, the optimization process had to end at some point, but it was concluded that further optimization could be made, however, this would mainly be for the benefit of cost rather than performance.

6.6 WP 6 Nacelle testing

The original thought of the WP6 was to test efficiency and lifetime. In the period of preparing the test rig, analysis were carried out, and the work of updating the multi body simulation and the finite element simulations of load distribution on the belts were made. This means that the nacelle testing ended up being a very high tech test with over 100 sensors located on the transmission. The reason being that the different analyses had shown new areas that would be valuable to understand in order to predict the lifetime of the belts.

7. Utilization of project results

The overall business plan remains. The timeline and milestones are subject to changes.
The nacelle testing in WP 6 will continue, after completion of the Global Team Turbine project. Additional functional test activities have been identified. These will be conducted over coming months where after endurance

test will continue for a period of time yet to be defined. Consequently the WP6, is likely to continue another 12 months.
Gates did file one patent during the project, but no further patent has been filed. Note that, many patents were already granted before starting the project. The project start up, was delayed primarily due to patent negotiations between Fred Olsen A/S and Vestas.

The Gates Corporation will continue the development and industrialization of belts for the Wind industry. Carbon reinforced timing belts in dimensions needed for the wind industry, are still being tailor-made at very low volumes in a prototype like production process. This has a negative impact on both cost and the technical capacities of the belts. This issue is critical to the potential commercial launch of belt driven products in the wind industry. To fulfill the requirements with regards to uniform product quality, warranty requirements and maintenance packages in a higher volume series production environment, further development of higher volume belt production processes will be key to success.

RWTH Aachen University is considering doing a PhD on dynamics on a belt drive

8. Project conclusion and perspective

The conclusion is that both technically and measured on cost efficiency, belt driven wind turbines is an attractive alternative to traditional geared wind turbines. The collaboration between partners will continue over coming years. Further technical evaluation is ongoing, and will continue uninterrupted by completion of the Global Team Turbine project.

The wind industry is still characterized by steady growth. The market is dominated by a few large wind turbine manufacturers (WTM), which all use direct drives or traditional gearboxes. Most WTM outsource the production of turbine gearboxes to a relative small list of providers with their preferred technology.
Even gearboxes for wind has gone through two digit number of design iterations, there are still considerable optimization opportunities for next generation gearboxes. Consequently gearbox design and integration optimization will still drive down LCoE over coming years. If major breakthroughs are realized in terms of the reliability, weight and cost, it might become more difficult to penetrate the market with belt-based drive trains.

The gearbox represents approx.14%(1) of the overall cost in a conventional wind turbine.
When installing a wind turbine, 73%(2) of total costs are from the turbine itself hence technology which lowers the cost of both the turbine and particularly the installation will be a heavy competitor to the market.

Belt drive transmission lies in the low cost of gear transmission, obtained through the whole life cycle – from low production costs to operation and maintenance. In addition, the lower weight of the nacelle and limitation of the impact of shocks and irregular loads contribute to minimize the maintenance costs.

Due to the lower complexity of the belt driven turbines compared to direct drive and traditional gearboxes, this technology will have a unique advantage in the emerging markets, where high complex and expensive components will be less competitive.

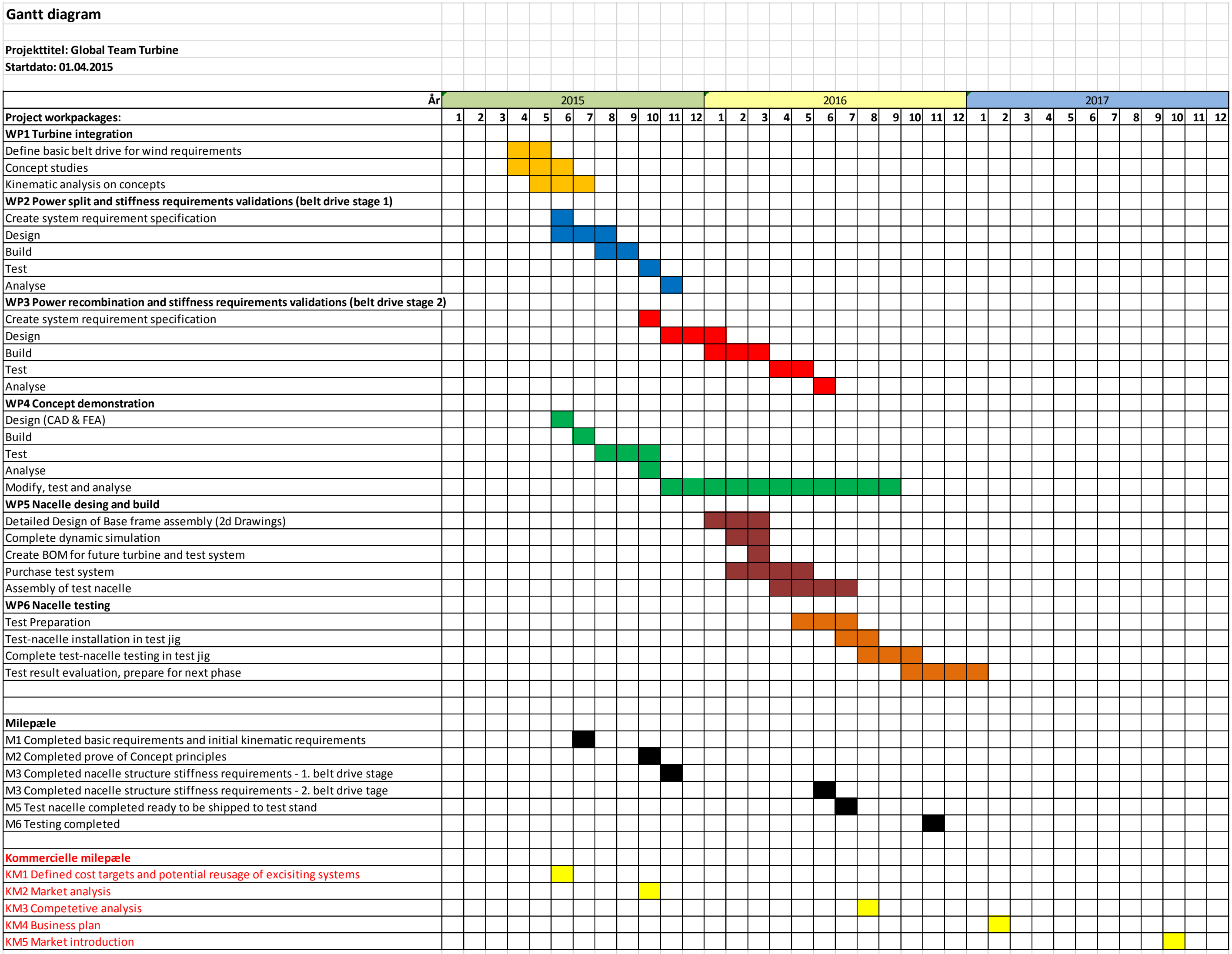
The actual market penetration plan has still not been defined. We may follow the steps described in the project application, but additional market and commercial analysis is to be performed before decision is being made.

The major barrier to emerging markets is the requirement of local content, to the highest Brazil demands that 60% of the wind turbine equipment must be sourced and offer subsidized loans to developers only if they do so. These barriers will be overcome as Vestas have established distribution channels globally and in some emerging markets such as Brazil, Argentina, South Africa even have existing sales and service offices. In the Indian market Vestas in addition to the sales and service office also have a production factory. The existing Vestas channels will be utilized and will facilitate access to market for the technology. The small turbine market is much more scattered with many small players. The gear systems in these markets are not stressed and engineered to the limit as gear system for MW turbines. Many of the smaller turbines are running oversized gearboxes from other industries.

The use of variable energy sources such as wind generates a security of supply issue. The most steady wind energy resources are found at sea. Therefore offshore wind parks play a large role in increasing the amount of renewable electricity in the system, while retaining security of supply. The main challenges here are the high investment as well as operational costs of today's turbines. The present project leads to both lighter and more efficient turbines with lower maintenance costs, resulting in both reduced investment and operational costs. This will enable a faster in-phasing of offshore wind energy leading to improved security of supply. The projects' contribution to accelerated increase of wind power installation will also assist the reduction of the Danish CO_2 emission. Last but not least, the wind energy industry will experience an enhanced competitiveness by being able to offer cheaper and lighter turbines with easier maintenance. These will be key competitive parameters for the companies' ability to penetrate new markets, especially in growth and developing economies. Target markets for the first turbine to be produced with a belt gear for some of the emerging markets. This will thus support the government's green growth strategy.

9. Annex

9.1 Project Plan

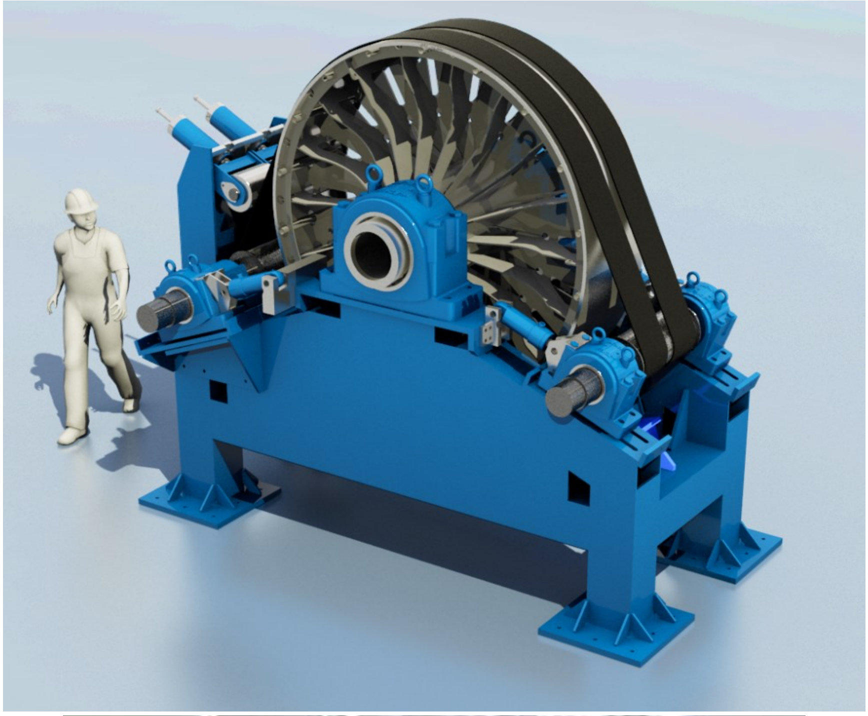


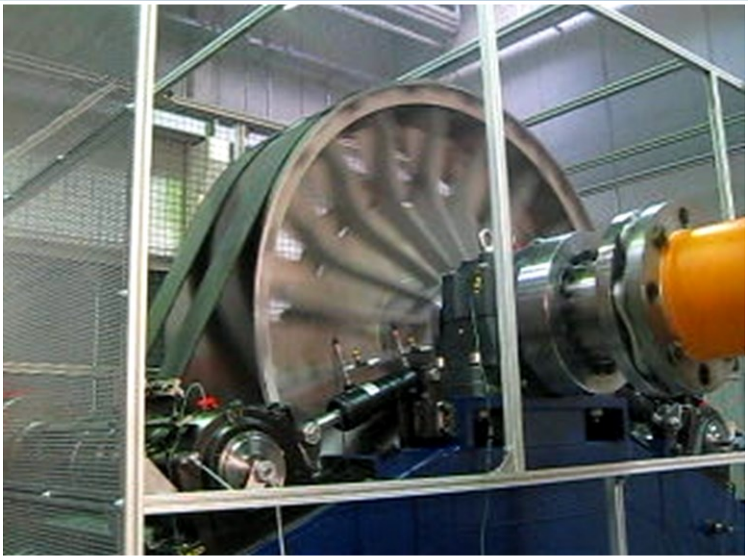
Vejledning: Udfyld ovenstående oversigt med navn på **work packages** og markér vandrette tidsforløb. Indsæt endvidere **nr.** og **navn på milepæle (tekniske og kommercielle)** og markér disse tidsmæssigt. Se evt. **eksempel Tilskudsportale** et Gantt diagram på Tilskudsportalen.

Milepæle: Ved milepæle forstås her afgørende delmål i et projekt for opnåelse af succes. Der vil i almindelighed være tale om et begrænset antal afgørende milipæle i det typiske projekt, typisk omkring 3-5 milepæle over et tre-årigt projektforløb. Kommercielle milepæle (KM) er aktiviteter i forbindelse med markedsfokus, markedanalyse, forretningsplan, konkurrence analyse, risikoanalyse osv. KM redegør for spørgsmål i forhold til markedsintroduktion, strategi, risikostyring, pris, distributionskanaler osv.

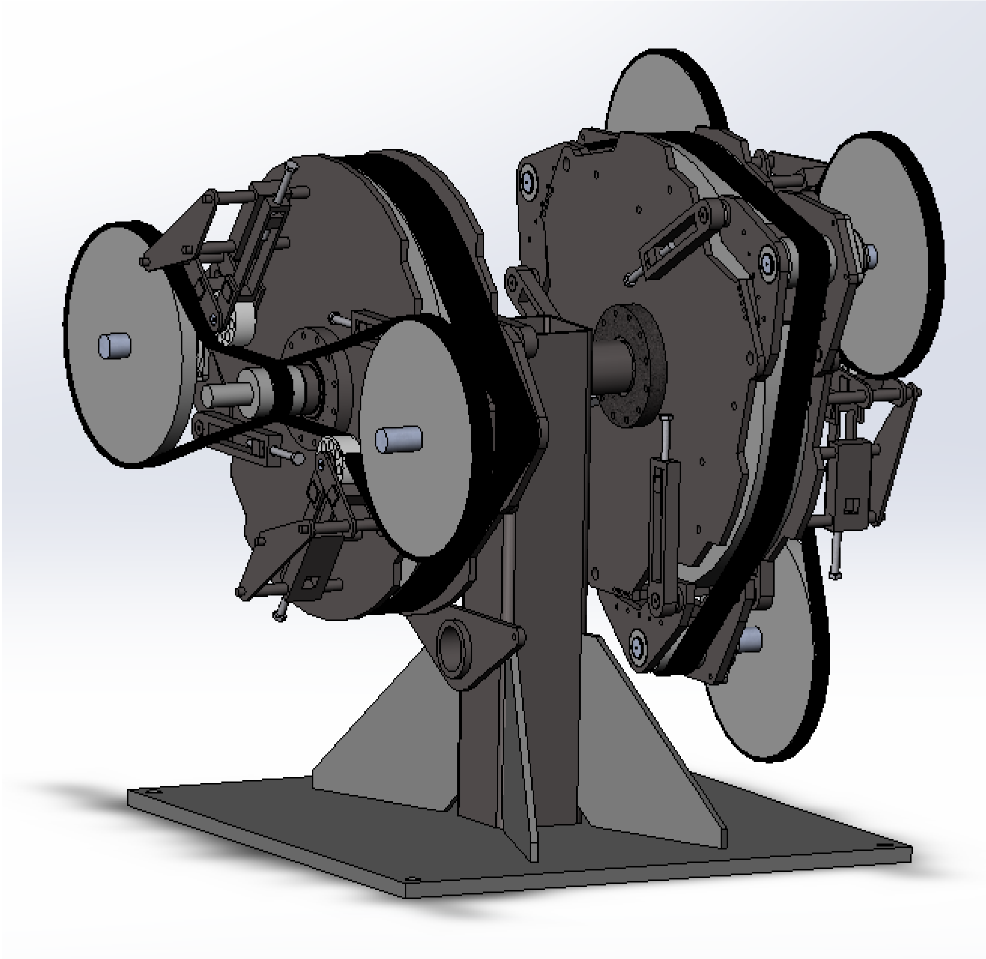
Dette skema er forberedt til op til 10 milepæle i alt

9.2 Pictures of WP 2 & WP 3 test set up – Aachen

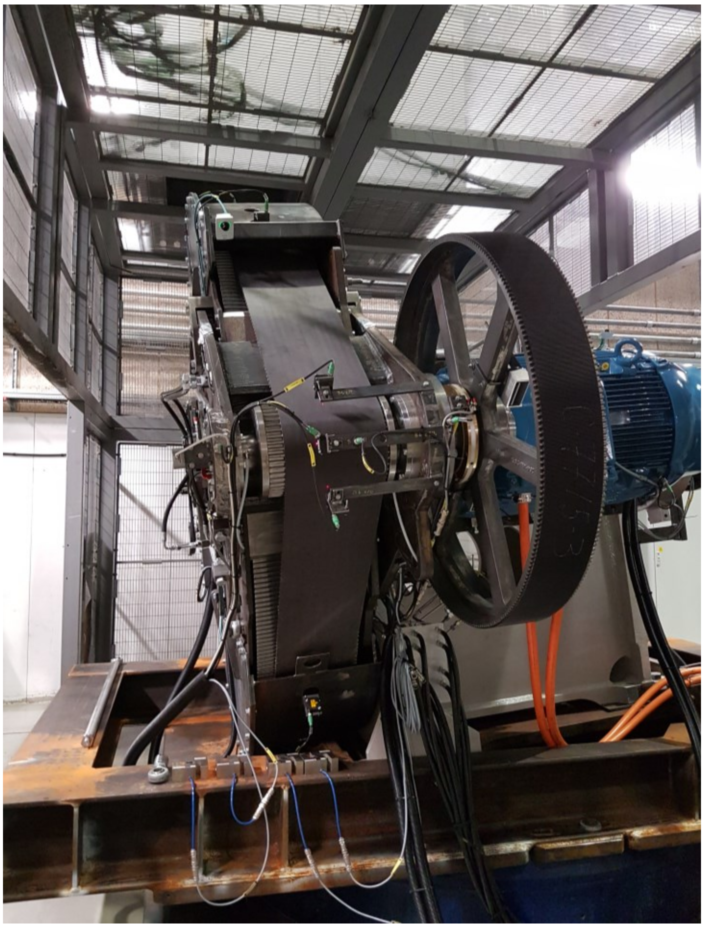




9.3 Pictures of WP 4 - Back to back test, Ringkoebing



9.4 Pictures of WP 5 + WP 6, Naecelle integration test, Ringkoebing



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