Final report

1. Project details

Project title	Validation of Industrial Active Aerodynamic Add-ons
File no.	64019-0061
Name of the funding scheme	EDUP – Generel pulje
Project managing company / institution	Siemens Gamesa Renewable Energy A/S
CVR number (central business register)	76 48 62 12
Project partners	Siemens Gamesa Renewable Energy DTU Wind Energy Rehau
Submission date	30 September 2022

2. Summary

English summary:

The project VIAs (**V**alidation of **I**ndustrial **A**ctive **A**erodynamic **A**dd-ons) aimed at demonstrating and validating the full-scale system integration of active flow control devices for the performance enhancement of wind turbines. An active flap system for rotor blades developed within the scope of the Induflap2 project, j. nr. 64015-0069 was integrated into a full-scale multi-Megawatt wind turbine for demonstration of turbine performance enhancement and load control. Furthermore, an improved design of the active flap component was realized and tested at laboratory level and partly at full-scale level. The integration of the active flap technology required the maturing of peripheral subsystems, in particular a pressure supply system, to a higher technology readiness level (TRL), development of novel measurement instrumentation and techniques, demonstration of manufacturing concepts suitable for serial production, development of full-scale turbine servo control strategies, increasing the level of integration readiness level (IRL), as well as performing a thorough system characterization both at laboratory scale and field test level. The project partners Siemens Gamesa Renewable Energy A/S, DTU Wind Energy, and Rehau A/S brought with them a high degree of expertise, experience, and professionalism, all of them being world leading companies / institutions in their individual fields.

The technologies in scope aims at increasing rotor aerodynamic efficiency, reducing turbine load levels, and increasing the authority of control of wind turbines through additional degrees of freedom in the control of power and loads. All this is done with the objective of increasing the cost and energy efficiency of turbines

leading to an improved ratio of produced energy to structural loading. The target of introducing such a technology on commercial wind turbines is to reach levels of improvement of the lower levelized cost of energy (LCOE) in the order of magnitude 4-6% together with an approx. 7% higher wind park capacity factor, which has a direct impact on the competitiveness of wind power in comparison with conventional energy sources. The active flap technology as such cannot be commercialized individually as it becomes a core area of the turbine once introduced into a given platform. The market potential of the active flap technology is therefore directly linked to the development of wind energy, in particular the development of offshore wind energy, and the link of such a novel technology (active flaps) into a new product which would increase the level of competitiveness of a wind turbine. Through the increased competitiveness and the lower LCOE, this project follows the European strategy of higher market penetration of renewable energies. The technologies developed have a direct impact on the position of Danish wind turbine manufacturers in the global market and maintains (and substantially improves) the leading position worldwide in terms of research and development in rotor blade technology, being all these well in accordance with EUDP's strategy.

Danish summary:

Projektet VIA'er (Validation of Industrial Active Aerodynamisk Add-ons) havde til formål at demonstrere og validere fuldskala systemintegration af aktive flow-kontrolenheder til forbedring af ydeevnen af møllens drift. Et aktivt klapsystem til rotorblade udviklet inden for rammerne af Induflap2-projektet, j. nr. 64015-0069 blev integreret i en fuldskala multi-Megawatt vindmølle til demonstration af last reduktion. Endvidere blev et forbedret design af den aktive flap komponent realiseret og testet på laboratorieniveau og delvist på fuldskalaniveau. Integrationen af den aktive flap teknologi krævede modning af perifere systemer, især et trykforsyningssystem, til et højere teknologisk readiness level (TRL), udvikling af nye måleinstrumenter og -teknikker, demonstration af fremstillingskoncepter, der er egnede til serieproduktion, udvikling af fuldskala mølle-styringsstrategier, forøgelse af niveauet af Integration Readiness Level (IRL), samt udførelse af en grundig systemkarakterisering både på laboratorieskala og felttestniveau. Projektpartnerne Siemens Gamesa Renewable Energy A/S, DTU Wind Energy og Rehau A/S bragte en høj grad af ekspertise, erfaring og professionalisme med sig, som alle er verdens førende virksomheder/institutioner i deres individuelle felter.

Teknologierne i omfanget sigter mod at øge rotorens aerodynamiske effektivitet, reducere møllebelastningsniveauer og øge kontrol muligheder af vindmøller gennem yderligere frihedsgrader i styringen af belastninger. Alt dette gøres med det formål at øge omkostningerne og energieffektiviteten af møllerne, hvilket fører til et forbedret forhold mellem produceret energi og strukturel belastning. Målet med at indføre en sådan teknologi på kommercielle vindmøller er at nå niveauer for forbedring af den Levelized Cost of Energy (LCOE) i størrelsesordenen 4-6% sammen med en ca. 7 % højere vindmøllekapacitetsfaktor, hvilket har en direkte indflydelse på vindkraftens konkurrenceevne i forhold til konventionelle energikilder. Gennem forbedret konkurrenceevne og lavere LCOE vil dette projekt følge den strategi Europa har lagt for højere markedsandele for grøn energi. Teknologierne som projektet udvikler, vil have en positiv indflydelse på den position Danmarks vindindustri har på verdensplan og vil være medvirkende til at fastholde dansk mølleindustri som førende i forskning og udvikling, hvilket er i fuld overensstemmelse med EUDP's strategi.

3. Project objectives

The objective of the project was to further develop, demonstrate, and validate at full scale active flow technologies for rotor blades of wind turbines. Part of the project aimed at a detailed validation of the active flap technology developed under the EUDP project Induflap2 (j. nr. 64015-0069). Furthermore, novel active flow control concepts developed internally at Siemens Gamesa Renewable Energy (SGRE) were validated at wind tunnel level. The main focus of the project was on the validation of an industrial solution for active flow control on rotor blades.

For the technically complex (and costly!) validation of the active flow control systems, novel measurement systems as well as a multi-scale validation approach (wind tunnel → rotating rig → field test) were required in order to characterize the aerodynamic, structural dynamic, and pneumatic response of the individual components. Furthermore, novel analysis and measurement methods were developed to cope with the requirements of this type of field test validation.

The work carried out in the project included the preparation of prototypes of active flaps (from Induflap2 design) together with further flow control developments at SGRE, followed by the installation of these active control devices on a SGRE turbine at Høvsøre. In parallel, new measurements devices comprising an inflow sensor, a wake rake and a surface pressure system were developed and tested at full scale on the turbine in campaigns in June 2021 and July 2022. These test campaigns enabled a detailed demonstration and validation of the performance of the active devices as the sectional aerodynamic performance can be derived and compared with wind tunnel experiments carried out at the wind tunnel facilities at DTU Wind Energy: Poul la Cour Wind Tunnel (PLCT). This kind of experimental data enables a new level of detailed model validation.

4. Project implementation

The VIAs project was executed overall according to the original plan in terms deliverables, milestones, and with a six-month adjustment (extension) of the timeline. The project was carried out in relatively turbulent times due to the Covid pandemic affecting almost the full duration of the project. Despite Covid and weather-related delays, all milestones were met and the project in general represents an important milestone in the academic and industrial world with respect to the validation of active flow control on wind turbines.

Never before, neither at national nor international level, had a research and development group taken the maturity of active flaps validation to a level comparable with the one reached during the VIAs project. The VIAs project led to the up-to-date largest (measured in terms of turbine power – 4.3MW) and longest (measured in terms of test duration of over 2 years) validation campaign of active devices publicly known. The learnings captured during the execution of this project will be of great value for future developments and product implementation of this technology.

At a more detailed sub-system level, wind tunnel and rotating rig tests have been successfully carried out serving as a proof of concept of the instruments and methods devised before they were tested at full-scale. During these activities, the first ever full-scale validation of a flap system with onboard autonomous data acquisition registering both angle of attack by means of a 5-hole Pitot probe, aero-dynamic loading (lift coefficient) by means of a 32-channel pressure belt, and aerodynamic losses (drag-coefficient) by means of a blade-mounted wake-rake was performed. These high-fidelity tests were performed in two individual test campaigns during June of 2021 and July of 2022. More details of the results are given in chapter 5. The full-scale characterization of the active flap system was performed in the period from end of May 2020 until end of July 2022 leading to a very substantial set of data for the active flap system.

The project members would like to highlight, that some of the developments and measurements carried out in this project are unique worldwide and represent the up-to-date most comprehensive field test program of an active flap system.

In parallel to the full-scale characterization of the first active flap design and using many of the learnings obtained from the sub-system and field tests, a new active flap system was designed, manufactured, and tested at wind tunnel and rotating test-rig level. A partial full-scale characterization for this new flap design was also performed during the spring and summer of 2022. The development of the new active flap design meets industrial requirements for manufacturing, service, and industrialization. The manufacturing of the components was demonstrated in industrial scale. The integration onto an existing blade has been demonstrated on an 8.6MW test turbine in Østerild. Some of its design characteristics will still need improvement in the future.

To improve the control of the active flap system, the VIAs project also worked towards an upgrade of the pressure supply system (developing a second and a third generation pressure supply concept), the control strategy of the flap, and of the methods and for integrating the flap system onto an existing rotor blade. All of these improvements led to a system with a faster response time and higher degrees of freedom in terms of turbine load control.

All validation activities were accompanied by the development of digital twin representations of the turbine which consisted of full detailed aeroelastic models of the turbine-flap system in the codes hawc2 and BHawC. The digital twin serves as a platform to test out flap load control strategies and thereby verify potential business case scenarios. Furthermore, all design activities were supported by the relevant multi-disciplinary simulations including finite element structural modelling (FEM), computational fluid dynamic simulations (CFD), and fluid-structure interaction modelling (FSI). Besides that, a large part of the prototyping efforts was based on efficient iterations leveraging on 3D printing technology.

Even though travel restrictions during 2020 and 2021 did not allow in-person workshops between the participants, weekly live-meetings kept the momentum of development activities high.

5. Project results

The original objective of the project was fully met, which overall was to validate the field performance and improve the sub-systems related to active flaps. A very graphic representation of the objectives of VIAs is shown in Figure 1. The extensive sub-system and full-scale validation activities lead undoubtedly to improvements of the technology, which will have to be implemented before the technology is ready for market introduction.

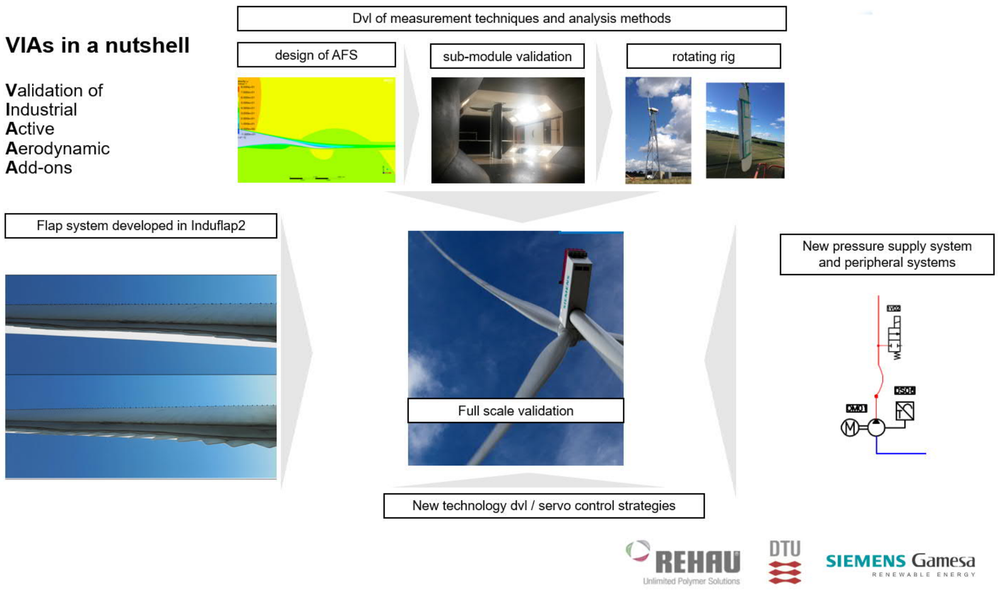

Figure 1. Project VIAs described in a nut-shell

The development of active flow control devices is a complex topic. Witness of this is the high amount of publication existing for decades already. Active devices for load control of wind turbine rotors have been extensively studied in the past. The interested reader is referred to the work of Barlas (2010), Johnson (2008), and Pechlivanoglou (2013), which in combination give a very good overview of the variety of concepts for wind turbine active and passive load control including active flaps, microtabs, as well as diverse mechanisms for boundary layer (BL) control such as BL suction and blowing, plasma actuators, or synthetic jets.

On the other hand, the amount of literature and studies available for system level full-scale experimental validation of active control strategies and devices is rather limited. In past publications of Sandia National Laboratories documented in the work of Berg (2014) within the scope of the SMART Rotor Project, where a 9m long blade with a hinged flap section covering the aft 20% of the chord of the outer 20% of the span was tested. The flap was actuated in a mechanical fashion with means of motors embedded in the structure of the blade. The characterization of the system was performed mainly via on-off actuation of the flap as well as sinusoidal actuation. A further full scale test was documented during the period from 2010 to 2014 through a series of publications by Castaignet (2010, 2013) and Couchman (2014) describing the test of a flap system on a Vestas V27-225 kW (13m long blade) equipped with a 70cm long trailing edge flap. During these tests, the turbine was operated in intervals with and without flap control swapping every 2 minutes. Recently, a shape conforming active flap (morphing trailing edge) developed within the framework of the EU INNWind project was tested under atmospheric conditions on the rotating test rig at the Risoe Campus of DTU by Barlas (2018). Parts of the text matrix included flap actuation steps, periodic feed-forward control based on azimuth position, as well as feed-forward control based on inflow angle. The flap step actuation is performed with cycles of 10s over a test period of 5 minutes, repeating this procedure for different pitch angles of the flap

When compared with these tests available in literature, it becomes clear that the joint efforts of SGRE, DTU, and Rehau, certainly have pushed the boundaries of the level of maturity of validation of active flow control devices at full scale. These full-scale validations include tests both on the rotating test rig at the DTU campus as well as active tests on a 4.3 MW turbine, and full scale installation on a 8.6 MW turbine.

5.1 Results of WP1: Development of measurements sytems

The main tasks of WP1 were

- Dvl and manufacturing of blade mounted inflow sensor
- Dvl and manufacturing of airfoil pressure sensing system (based on surface-flush pressure sensors as well as existing commercial systems)
- Dvl and manufacturing of drag sensor (based on a blade mounted wake rake technology)
- Dvl and manufacturing of autonomous data acquisition system

These sensors (i.e., the pressure belt, the inflow sensor, and the drag sensor) were designed, manufactured, and tested at different levels of fidelity ranging from wind tunnel measurements and up to full-scale measurements on a 4.3MW turbine with the purpose of increasing the level of fidelity of the characterization of the active flap system. Accompanying these sensors, an autonomous data acquisition system was designed and adapted in order to collect in the different test environments. A view of the pressure belt as tested in the wind tunnel is shown in Figure 2.

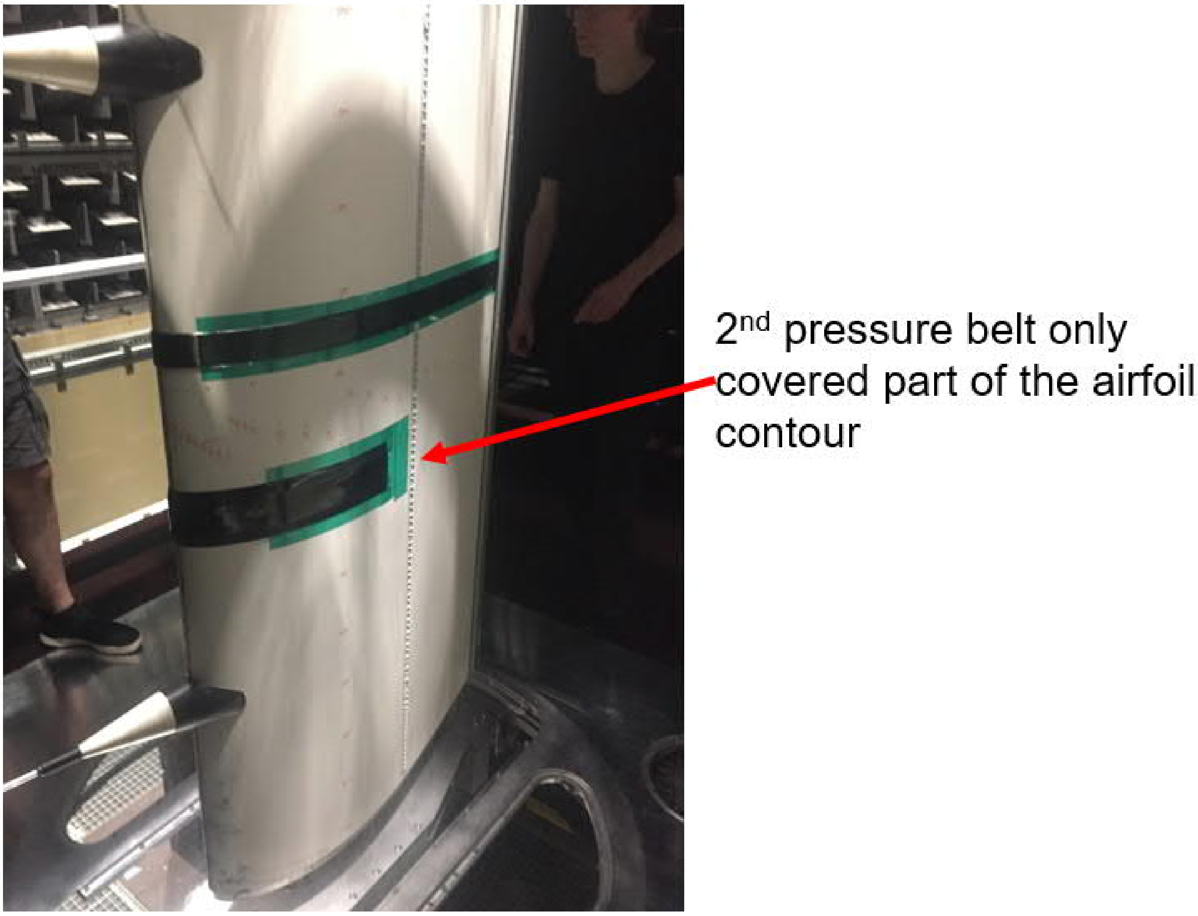

Figure 2. View of the pressure belt being tested in the wind tunnel.

The system was tested in two independent wind tunnel campaigns, rotating test rig campaigns, and two independent full scale testing periods at full-scale. The full-scale tests of the pressure belt, the inflow sensor and the data acquisition system on were carried out on June 9-10, 2021 on the Siemens Gamesa turbine SG-DD-120 4.3MW turbine at Høvsøre. The details of this measurements have been published by Madsen et al (2022).

The full-scale test of all previous sensors as well as the wake rake was carried out on initially on the rotating test rig at the Risø campus of DTU Wind Energy and subsequently on July 27-28, 2022 in full-scale on the SG-DD-120 4.3MW. The results are still to be published in a suitable conference. An overview of the designed and tested wake rake system is shown in Figure 3 below.

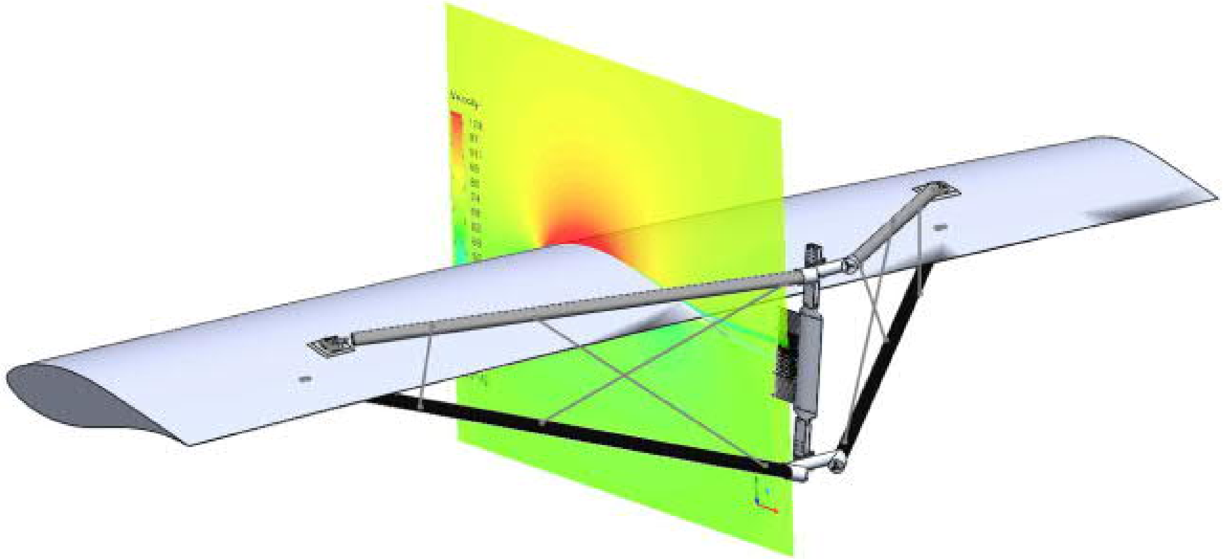

Figure 3. View of the design of the wake rake prior to test at full scale in July 2022.

5.2 Results of WP2: Development and manufacturing of active flow control devices

The content of WP2 is related to the following topics:

- Concept catalogue and final selection of candidates for new active flap design
- Design of device integration into rotor blade
- Design / design update of aerodynamic devices
- Manufacturing of aerodynamic devices
- Demonstration of manufacturing process for serial prod.

The design of a new active flap component taking into account the learnings of the first design was based on a multi-disciplinary approach including CFD and FEM simulations, 3D printed prototypes as well as functional tests. The project partners did a large effort towards designing the detailed geometries of the different components which are included in the active flap (not shown due to confidentiality reasons). The components of the active flap system are made up independently manufactured components, all of which have been manufactured with a technology demonstration suitable for serial production and assembled as prototypes for the testing required during the project. The new active flap is an improvement with respect to the previous design, making it a more mature system which can be scaled up in industrial scale and is suitable for servicing, serial manufacturing and installation. The assembly method of the flap has been proven by assembling close to 200m of active flap sections, and the integration method onto an existing blade has also been proven by test installation on an 8.6MW test turbine. This test was mainly for proof-of-concept purposes. The main validation activities took place on the 4.3MW turbine.

5.3 Results of WP3: Demonstration, test, and system characterization

The individual tasks of WP3 are summarized below.

- Definition of measurement program
- Design of smart airfoil wind tunnel section
- Wind tunnel verification
- Rotating test-rig verification
- Design and manufacturing of peripheral sub-systems
- Control software for peripheral sub-systems
- Turbine installation and instrumentation
- Full scale system demonstration

The results of WP3 are certainly the most comprehensive of the full project including the demonstration, test, and system characterization at different levels of fidelity ranging from wind tunnel level up to full-scale level, as well as including the development of the required peripheral systems to be able to carry out the tests.

During three wind tunnel test campaigns, different flap designs and other active flow control devices based on spoiler technology were tested. These devices are tested at different wind speeds and at a number of different deflection angles in order to span as much as possible of the operational envelope of the active flap system. The main purpose of the wind tunnel tests is to test the aerodynamic performance of the different designs and check the load performance of the pressure activation system of the flap under realistic aerodynamic loads. Some tests were also dedicated to the development and validation the pressure belt that is used to measure the pressure distribution on the test turbine in the full-scale flap tests.

Figure 4. Second generation of pressure control system.

Figure 5. Third generation of pressure supply system and control box.

As a part of this work package, the pressure supply system was been updated initially to a second generation for faster system response (control hardware box shown in Figure 4). Subsequently, the pressure supply system was updated to a generation 3 with control routines allowing for control of three flaps in a cyclic activation (hardware shown in Figure 5).

Furthermore, the instrumentation installed on the turbine (strain gauges, accelerometers, wind sensors, etc.) complemented the tests performed for the characterization of the sensors developed in WP1. As an example, Figure 6 and Figure 7 show the test of the wake rake in a rotating test rig environment and the test of the pressure belt and inflow sensors at full-scale, respectively.

The active flap system was been in operation on a SG 4.3-120 DD turbine in the period from May 2020 until end of July 2022 (see installation in Figure 8), making it in this way the world-wide longest test of active devices on a commercial wind turbine. The tests were performed at the test center Høvsøre (see Figure 9), with additional instrumentation provided by SGRE including a meteorological mast (met-mast) and Lidar wind speed measurements.

During the test period, tests were performed in order to characterize the system under different atmospheric conditions in order to measure the potential of the active flap as a load handle for the turbine for the purpose of load control. The results of this characterization were published by Gomez Gonzalez et al (2022). Some validation tests were also used for characterization of the digital twin of the active flap system and were published by Gamberini (2022) in collaboration with Gomez Gonzalez and Barlas from SGRE and DTU, respectively.

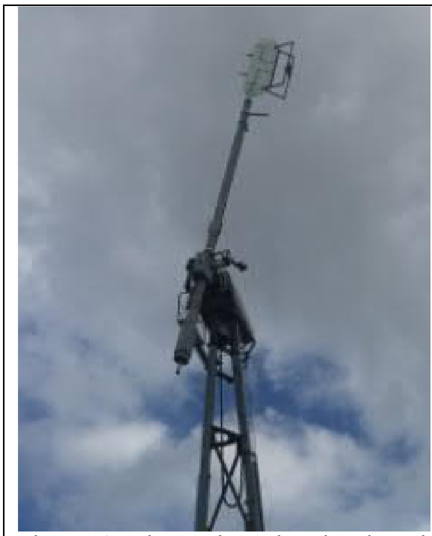

Figure 6. The wake rake developed within the INDUFLAP2 project for measurements of the drag on a rotating blade section. Here the rake is attached on a 2.0m blade section mounted on the rotating test rig at the Risø Campus at DTU.

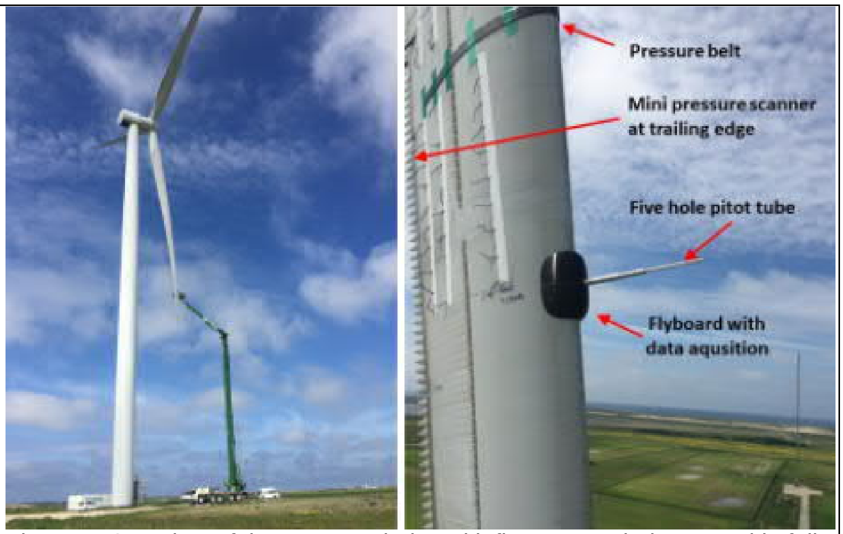

Figure 7. Overview of the pressure belt and inflow sensor being tested in full-scale in June 2021.

Figure 8. View of the active flap system during characterization tests of instrumentation systems

Figure 9. SG 4.3-120 DD turbine used for full-scale characterization of the active flap system in the test site Høvsøre.

5.4 Results of WP4: Validation of aeroelastic model simulations

The main tasks of WP4 are summarized below:

- Development of the measurement methods for the fullscale system characterization
- Data analysis and performance characterization of active flow control system
- Deriving the 'digital twin of the full-scale system'
- Load calculations

This work package included the definition of aeroelastic models (digital twin), the load calculations for business value evaluation in terms of load reduction, as well as the data analysis from WP3.

The main activities of WP4 are basically the diverse aeroelastic calculations which compliment all flap design and validation activities.

Initially, the aeroelastic model of the SG-DD-120 test turbine at Høvsøre ('digital twin') was developed in both in-house tools of DTU (HAWC2) and SGRE (BhawC), and initial verification and comparison were performed. Load simulations were performed and compared with the results of the measurement campaign. An example of such comparison in shown in Figure 10 and was published by Gamberini (2022) in collaboration the DTU and SGRE. The development of numerical models in an aeroelastic environment for the full turbine including the active flap was finalized and both codes can be considered state of the art in terms of aeroelastic calculations with active flow control devices.

The results in Figure 11 show the high level of agreement between both simulation tools and the experimental data.

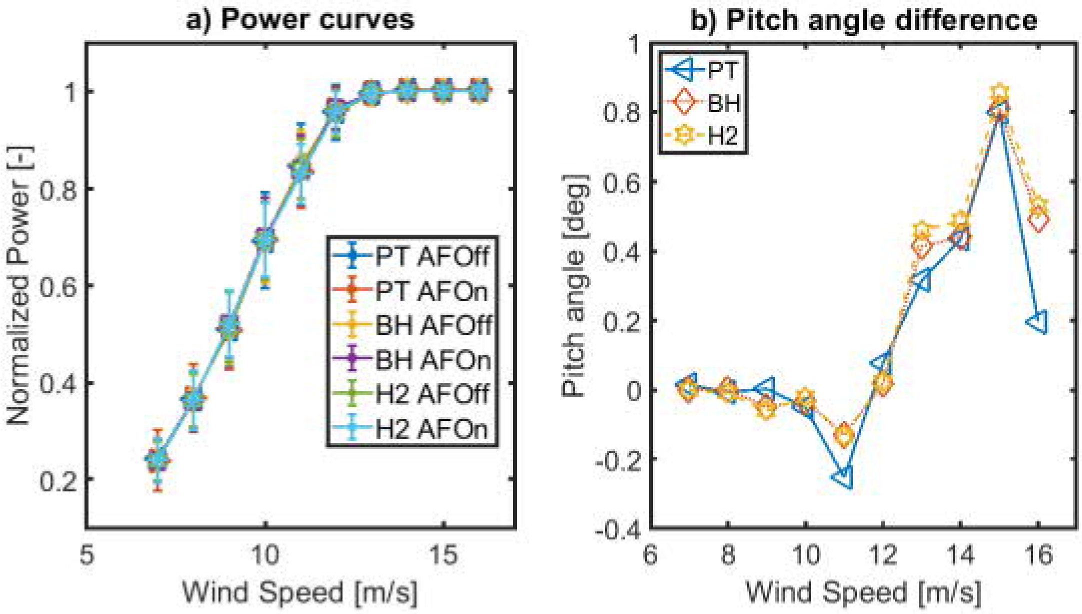

Figure 10. Power curve and pitch angle difference comparison between measurements (PT) and both aeroelastic / digital twin models with BHawC (BH) and Hawc2 (H2). Reproduced from Gamberini et al (2022)

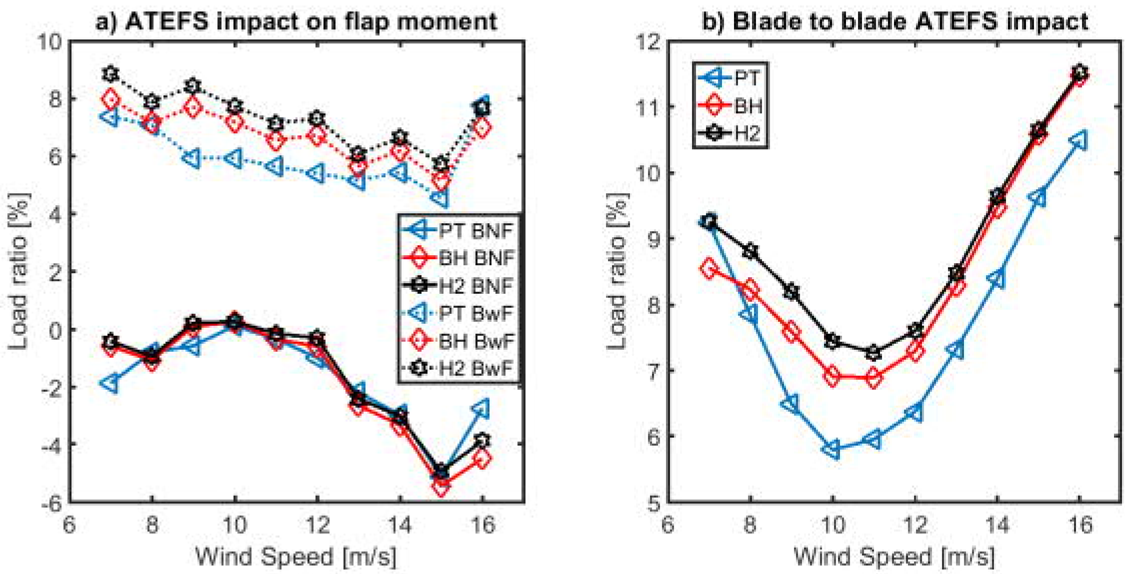

Figure 11. Blade bending moment comparison between measurements (PT) and both aeroelastic / digital twin models with BHawC (BH) and Hawc2 (H2). Reproduced from Gamberini et al (2022)

5.5 Results of WP5: DFMEA and risk evaluation activities.

The main tasks of WP5 consisted of the following:

- Business case scenario definition
- Technology demonstration for different business case scenarios
- Update DFMEA of active flap system
- DRA of active flow control technology

Within this work package, the activities have focused on the evaluation of business case scenarios via load calculations and demonstration. Furthermore, this WP included an update of DFMEA and risks of the active flap technology which was used as input for the redesign of the active flap system.

One of the main results from the data analysis of the field tests was the characterization of the active flap system in terms of its load response in steady-state and cyclic mode. These results are shown in Figure 12 and Figure 13, respectively.

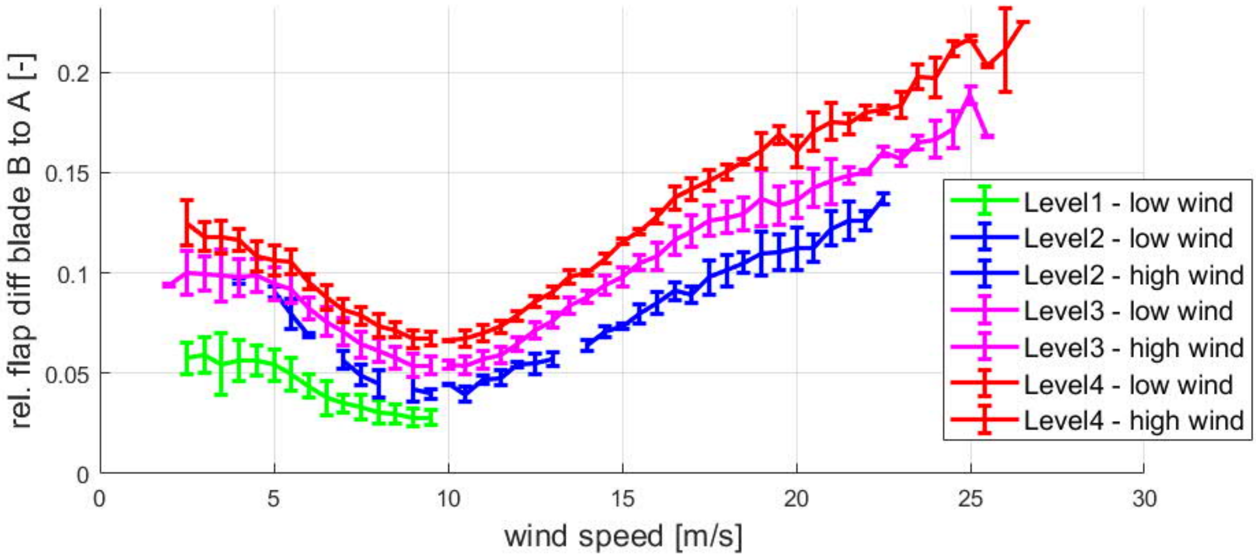

Figure 12. Measured load handle of the active flap system at different levels of operation

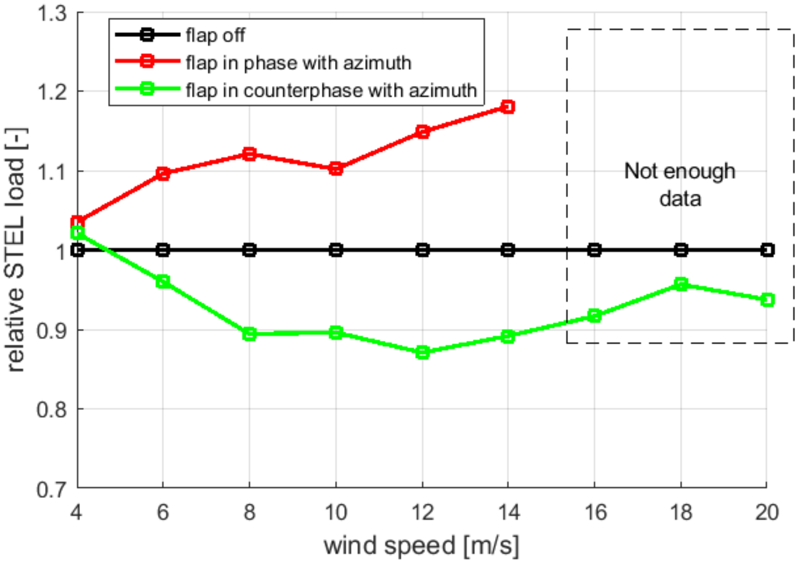

Figure 13. Measured load handle for blade fatigue reduction with the active flap system at different levels of actuation.

These results can be summarized in the following way:

- Clear impact of active flap system (AFS) on mean loads validated for different activation levels (angles)
- Blade root bending moment load handle between 3-20% depending on wind speed and AFS activation level
- At high windspeeds, the relative impact of the AFS becomes higher (same AFS load handle, but lower mean thrust and blade bending loads)
- Clear impact of AFS on fatigue loads validated (both increase and decrease depending on relative 1P phase shift)
- 1P load handle measured up to ~20%
- Blade fatigue loads decreased by 5-12% (depending on wind speed)

5.6 WP6 - Project Management

The work performed within WP6 relates mainly to the project management, organization of workshops, meetings, project internal communication and reporting.

A good lesson learned during this project is that it is crucial for a positive outcome of a project to maintain continuous open communication channels. Weekly meetings, despite the time consumed, maintain the project participants aware of the developments of the different work packages and were very useful for problem solving and overcoming issues both related to technical and non-technical aspects of the project.

Furthermore, a good lesson learned of the project is that testing in early phases of the development leads to a large amount of learnings which feed in directly into redesign of components. Leaving the sub-component and field testing to the end phases of a project is a recipe for failure.

Further lessons learned of the project include

- Get experience from real tests and not base evaluation solely on simulations
- It is good to use rapid prototyping, e.g. 3D prints, as it gives a completely different dimension in the understanding of a design
- Align with all partners on regular meetings – at a minimum bi weekly and in sprints periods either every day or every second day when test campaigns are coming up
- Good to perform regular wind tunnel test to support ideas and modelling
- Timing of reporting is important to avoid overhead time in reports/presentations and to avoid “forgetting results” if these are not reported in a timely manner
- Continuous follow up of technology requirements and make modifications to the design accordingly
- Aim at having design specifications as clear as possible

6. Utilisation of project results

The results of WP1 are mainly used by DTU for the validation of the instrumentation developed. This instrumentation can be used in the future for commercial offering of such measurement services. Furthermore it serves as basis for the validation of more advanced active flow control devices, or for more comprehensive validation of turbine operation which is of high value for OEMs.

The results of WP2 are mainly used by Rehau, where the industrialization process developed served as a basis for manufacturing active flap components which can be installed on offshore wind turbines, which is the core business of SGRE. It is expected that the turnover of both Rehau and SGRE will increase when this technology is introduced in the marked. Nevertheless, the market introduction of such a technology is linked to the product roadmap of the manufacturer (in this case SGRE), and for that, all risks of the technology need to be minimized also in aspects not considered within this project (e.g. service, repairs, supply chain, factory installation, etc) and the redesign aspects identified in this project must be carried out accordingly. After successful market introduction, it is expected that an initial fraction of the offshore fleet of turbines can be designed including this technology. This technology needs to be introduced into a product already during the design phase, meaning that it cannot be retrofitted onto existing products. Due to this, the timing of market introduction is linked to the target of product releases by SGRE.

Apart from that, other aspects of the technologies developed by DTU, SGRE, and Rehau in terms of modelling, measurement, validation, and serial manufacturing of active devices is generically applicable to various types of offshore wind turbines and is not limited to specific platforms.

Sales of turbines including this technology will not be straight forward, as mature customers will always ask for track record in order to reduce the risk. This means that further validation will most certainly be required until the active flap technology reaches a risk level which is low enough for the “general customer landscape” to accept it. To overcome these difficulties, it is the task of the OEM (Siemens Gamesa) and the product manufacturer (Rehau) to engage in close conversations with the potential customers of these offshore turbines, to make sure that all relevant risks are addressed correctly. Due to the nature of this technology, it has not yet led to turnover. This has to do, as explained, with the fact that such a technology needs to follow offshore platform developments. The offshore market, due to its “inertia”, is a slow development market. Nevertheless, the potential of this technology is very high, and the project partners are positive that it will lead to a very positive outcome in the future.

As of today, no competitive technologies exist in the market. The consortium of SGRE, Rehau and DTU are clearly world leaders in this sector of active flow control for wind turbines. This situation can always change if other participants of the offshore market come up with similar solutions.

7. Project conclusion and perspective

With the VIAs project coming to an end, all activities and milestones have been successfully reached. In particular the last year of the project was extremely exciting, including the continuous field characterization of the active flap system, the manufacturing of an upgraded flap component, successful test of a new pressure supply system, lab and full-scale tests of new instrumentation and analysis methods, as well as the aeroelastic validation of measurements vs simulations on a digital twin of the turbine.

A pneumatic active flap system was designed, manufactured, and successfully tested at different levels of fidelity and complexity, starting with sub-system tests at wind tunnel level, and finalizing with full scale validation on a SG-DD-120 4.3MW turbine. Wind tunnel measurements and field validation experiments provided input for carrying out relevant aeroelastic simulations of the system. The level of variation of the aerodynamic characteristics measured is deemed to be very significant in order to provide an active load control system with enough authority of control for adjusting the loading level of the wind turbine.

The Active Flap System underwent field testing from May 2020 until July 2022. These results build on top of the development activities started in 2015 as part of the Induflap2 project. The resulting load handle levels for the flapwise bending moment has been measured to be between 3% and 20% for steady state loads, and in the range of 13%-18% for fatigue loads depending on the type of actuation.

The load handles measured are certainly very interesting from a wind turbine design perspective. Such load handles can be used in two ways: the first one is during the design phase of a new platform in order to enable a more cost-effective dimensioning of the main components, and the second one is to upscale the rotor of an existing platform while maintaining the loads within the allowable envelope, having thus a positive impact on LCOE.

The measurements performed were accompanied with high fidelity aeroelastic simulations where the aerodynamic input was based on polars measured in a wind tunnel, and the atmospheric inflow was based on met-mast and lidar measurements. Very good agreement was found between the measurements and the simulation results.

The field tests of an active flap system carried out within this project are unique world-wide both in terms of its size (largest turbine ever where an active flap system has been tested – 4.3MW) and the duration of the test period (2+ years). Such a milestone would not be have been feasible to achieve without the very strong academia-industry partnership present in this project, and the economic support given by EUDP.

During its duration, the project has also done a good job in terms of dissemination, participating with several publications in some of the most renown and respected academic conferences within the field of aerodynamics and aeroelasticity. Furthermore, results were also shared in the commercial forum Wind Denmark 2021, as well as for general audience in the form of LinkedIn posts.

The technology of active flaps has come several steps closer to becoming an industrial solution through the demonstrations of manufacturing and full-scale testing. Testing is always accompanied by challenges and unknowns, leading to new learnings which can be fed back into the design of the product in order to improve its robustness. Such learnings have been very valuable during the test-phase of the VIAs project and will be fed back in the design loop for upcoming generations of active flap systems.

The project partners strongly believe that this technology can be a stepping stone towards the design of more cost-efficient wind turbines in the future.

Some “soft” conclusions of the collaboration work between the partners are:

- Experimental and numerical validation work best when they go hand-in-hand
- Close collaboration between academia and industry is a key element in the development of this type of technologies
- There is a need for new technologies to enable future blade designs (design driver landscape changes constantly)
- Is the active flap technology mature enough? No, but we certainly brought it much closer than nobody else before. Does it have future potential? Certainly.

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