

Smart Rotors for Cost Efficient Wind Turbines

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Abstract

By the end of 2015, wind turbine power plants with a total output of 430 GW were installed worldwide, more than 43 GW in Germany accounting for roughly 14% of its national gross electricity generation. Essential advantages of wind energy are low electricity generation costs, global applicability and good controllability (especially concerning system services).

One of the most important objectives of research and development is further cost reduction. Further developments in plant engineering are necessary for this. Weight reduction and a longer life, achieved through new construction methods and the use of new materials, and taking into account the system parameters regarding elasticity and structural dynamics, are essential drivers in cost reduction. This contribution explores the research into innovative rotor blade technologies within the scope of current research projects in the framework of these topics.

New methods covering areas from the design process to automated production, the behavior of new components in the overall wind turbine system and the impact on acceptance criteria (such as noise) must be verified and validated before they can be used in industrial operation. For this, the construction of a research platform (DFWind), funded by the BMWi and the state of Lower Saxony, is going to provide an infrastructure in the coming years. This infrastructure shall allow the testing and qualification of new technologies and methods in addition to the phenomenological investigation of two – in main wind direction consecutively placed – wind turbines and their surroundings.

1. Introduction

The production of wind energy comes with several advantages as the ones mentioned above, however there are many challenges that need to be overcome in order to be able to build bigger generators capable of fulfilling international and national demands for energy. Some of these challenges are related to costs and production, such as maintaining low costs compared to other sources of energy while providing with equal amounts of power and capacity, or building larger rotor blades while remaining light enough, feasible and economical; other challenges are related to acceptance from the population, such as producing larger wind turbines that are quiet enough to be able to be installed near to urban or rural settings. In order to be able to fulfill these challenges, different types of technologies must be explored and further developed. This contribution explores the research into innovative rotor blade technologies within the scope of current research projects and provides an outlook towards future technologies.

2. Motivation and Goals

Wind energy in Germany and in the world is continuously growing. More power is being generated, the amount of available wind turbines is increasing and their size and therefore power generation capabilities are also increasing. According to the GEWC Global Wind Report [1], by the end of 2015, wind turbine power plants with a total cumulated output of 430 GW were installed worldwide, following a growing tendency. As it can be seen in Figure 1, this trend has been also followed in Germany over the last 25 years, where more than 43 GW were installed Onshore by the end of 2015 [2], accounting roughly for 14% of the gross global value.

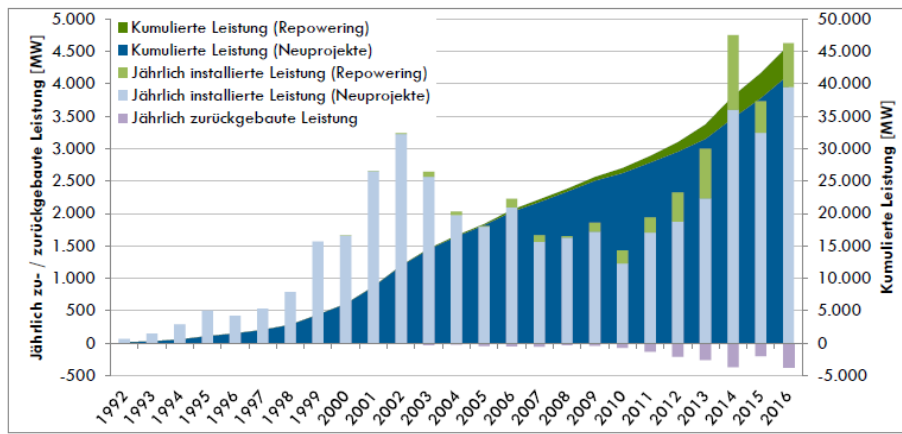


Figure 1: Development of the yearly installed, decommissioned and accumulated onshore wind energy output [MW] in Germany (Status 31.12.2016) [2]

In addition to these global tendencies, the fact that the production of wind energy provides some essential advantages such as low electricity generation costs, global applicability and good controllability, contributes to the probable maintenance of this trend in future years. Furthermore, according to the “Leitstudie 2010” [3] presenting long-term scenarios and strategies for the expansion of renewable energies in Germany, the amount of power generated through wind energy, compared with other energy sources (such as photovoltaic, natural gas, oil, hydraulic, etc.), will significantly increase.

For this trend to actually be achieved, and, with the increase in production and a growing tendency towards larger rotors (Figure 2), new and important challenges need to be overcome, such as the development of new types of structures capable of withstanding the higher loads while remaining lightweight; or, gaining adequate levels of acceptance from the public, e.g. regarding noise production due to larger operational speeds at the blade tips. In addition to the technical challenges, one of the most important aspects to overcome remains however costs. Because of this, one of the main objectives of research and development is further cost reduction and, for this purpose, further development in plant engineering is necessary [4]. Weight reduction and a longer life achieved thanks to new construction methods and the use of new materials; taking into account the system parameters regarding elasticity and structural dynamics, are essential drivers for achieving these goals.

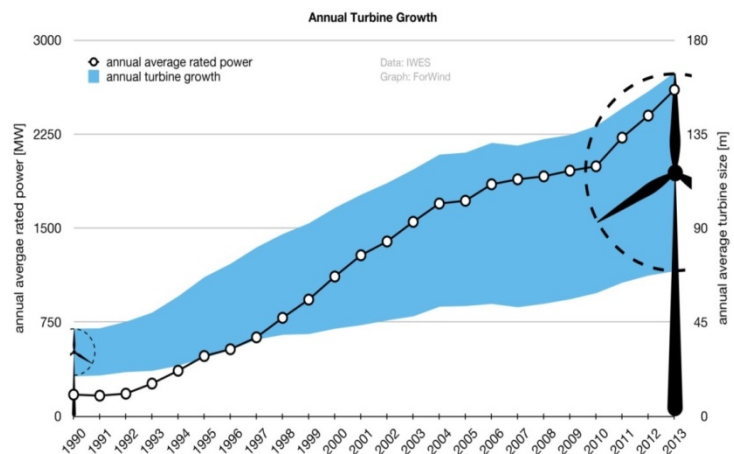


Figure 2: Wind Turbine size growth in Germany [18]

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The following sections present an overview of current research activities aiming to develop a new generation of wind rotor blades, using new materials, new design principles and new technologies for building wind turbines at lower costs and with higher levels of acceptance.

3. Smart Blades

Within the frame of the so called “SmartBlades” project three technologies for enabling the design and building of larger rotor blades capable of adapting themselves to variable wind conditions; of standing gust loads in diverse environments; and at the same time, capable of generating more power, while remaining light enough to be feasible, transportable, mountable and keeping lower costs, were studied. Figure 3 presents an illustration of some concepts.



Figure 3: Scheme of a wind turbine with smart blades technologies [DLR]

Bend-Twist Coupling

The first technology investigated within SmartBlades studied the coupling of bending and torsion of the structure, aiming to enable the blades construction of adjusting themselves to variable wind conditions in a passive manner. This means the blades can twist themselves along their span in order to achieve an optimal angle of attack, providing for example with a larger surface for good performance at lower wind speeds; and with a smaller exposed surface when strong winds are raging, preventing damage.

The bend-twist coupling can be achieved through a variation of the blade’s geometry through sweep. Figure 4 presents an example of a discretized model of a straight (blue) and of a swept (black) blade.

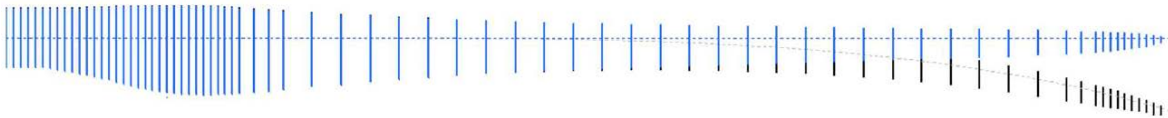


Figure 4: Discretised model of the straight and the swept blade [5]

The change in geometry achieved through sweep introduces a coupling coefficient, κ , for the structural behavior of the blade. This coefficient can be calculated by dividing the torsional moment, M_t , by the flapwise bending moment, M_b , at the section [5]:

$$\kappa = \frac{M_t}{M_b}$$

The studies for introducing a geometrical bend-twist coupling by sweeping the blade demonstrated that the concept is a feasible option for achieving a passive load reduction for the rotor blades from a structural point of view. It was shown that by changing the torsional deflection of sections (i.e. the angle of attack of the airfoil) with regard to the flapwise bending moment the aerodynamic coefficients can be adapted at the blade, without a need for using additional blade pitching or further active flow control systems.

In addition, Figure 5 presents some of the results of a parametric design study of bend-twist coupling blades, which show that the use of this technology contributes to the reduction of fatigue loads over the blade’s lifecycle.

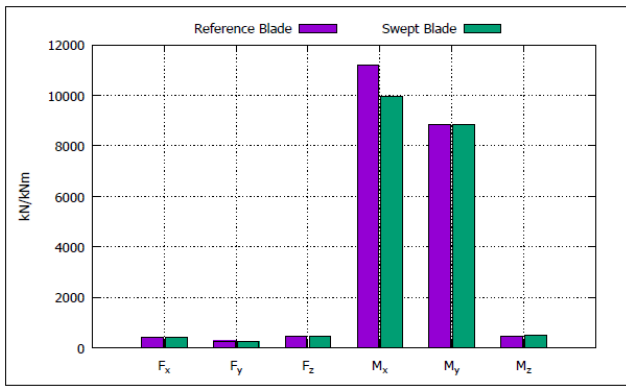


Figure 5: Fatigue DEL at blade root [16]

Basing on these results, questions remain open regarding how smart blades manufactured with this technology, at a representable scale, would stand testing under static and dynamic conditions and also under real environmental conditions, in order to help examining the behavior and integrity of the new design as well as demonstrating the technology's efficiency.

The measurement results from such tests could then be used to validate design and simulation methods developed during the SmartBlades project and to improve and further refine them. This helps to determine

the economic potential of the bend-twist smart blade concept and lead to the achievement of a higher technology readiness level, supporting industry on its path towards manufacturing bigger, more powerful and more efficient wind rotor blades in mass production processes.

Trailing Edge Flaps

Another SmartBlades technology focuses on the use of active elements, capable of modifying the trailing edges of the blades in a controlled manner, a technology inspired from aircraft high-lift devices and control surfaces (Figure 6) [6]. The main advantage of the system is its ability of changing the airfoil's shape in a rapid manner, allowing highly inertial blades to adapt themselves to quickly and strongly varying wind conditions, such as gusts, and improving so their performance under diverse circumstances.



Figure 6: Trailing Edge Concept Demonstrator [6]

Design and control strategies for the implementation of the concept were studied within the SmartBlades project, including the conception and realization of a lightweight flexible trailing edge demonstrator for wind energy turbines; a comparison of individual pitch and trailing edge flap control for structural load mitigation under normal operating conditions in a wind turbine; and an investigation on various possible configurations for effective load reduction.

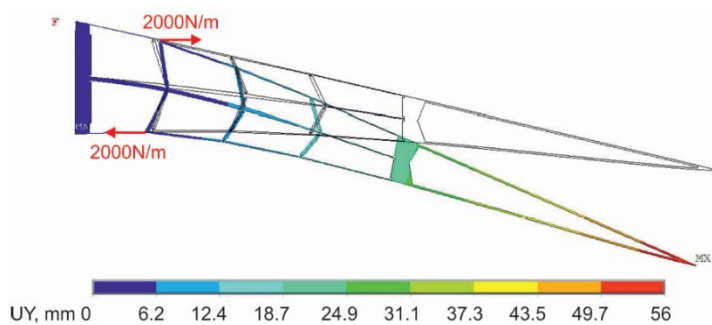


Figure 7: 2D finite element based displacement plot of flexible trailing edge concept [6]

The approach for the design of a flexible trailing edge was based on a GFRP middle plane carrying the trailing edge's loads. This plain must be flexible enough for achieving the desired trailing edge's deflection, but simultaneously remaining robust enough to stand the aerodynamic loads.

The results of a finite element study (Figure 7) were verified with the help of a 0.3 m span specimen of such a flexible mechanism [6]. In

addition larger test segments were prepared for tests under centrifugal loads.

The main objective of such rotating tests is to prove that the concept can reach the desired aerodynamic and mechanical effects while standing loads that would be experienced under real loading conditions, such as centrifugal forces and common weather impact. The measurements resulting from these tests could then be used for the validation of simulation models accounting for fluid structure interaction that were originally used for predicting the behavior of the structure under real conditions. This would enable the implementation of the system concept in full scale rotor blades.

In addition to the rotating tests, the aerodynamic behavior of the used model should be tested in a wind tunnel, in order to study the influence of the trailing edge deflection on the polars of the blade segment demonstrator, allowing a final validation of the aerodynamic simulation results.

Control strategies for the trailing edge system were also studied. Different combinations of individual blade pitch and trailing edge flap control to alleviate the frequency components of the flapwise root bending moment, which occur once-per-revolution (1P) and twice-per-revolution (2P) in the rotating frame of reference were implemented [7]. For this, a H_∞ loop shaping design was developed based on a simplified wind turbine model. This control method allows achieving stabilization with guaranteed performance by solving an optimization problem for the control system. In the case of the flap, lifetime damage equivalent loads were evaluated on several wind turbine components to define best controller combinations. It was shown that the maximum load reduction of the flapwise blade root bending moment can be achieved with the combination of individual pitch and trailing edge flap control. Figure 8 shows an example of results obtained for the flapwise blade root bending moment control for 1P and 2P.

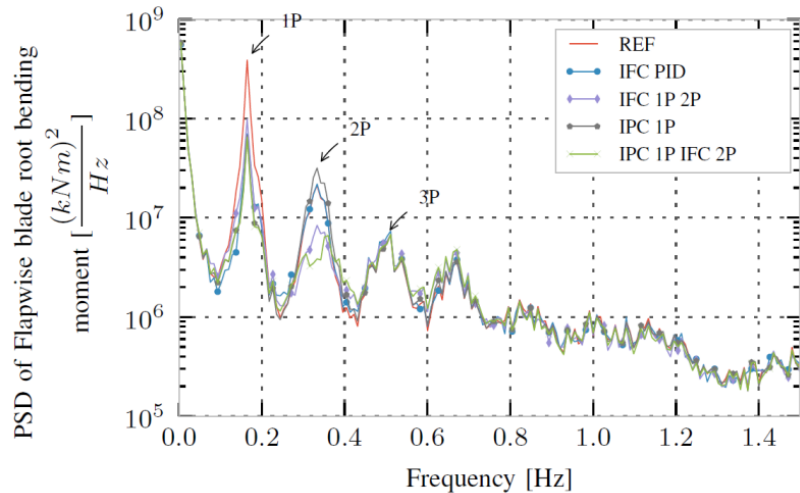


Figure 8: Power spectral density of the flapwise blade root bending moment [7]

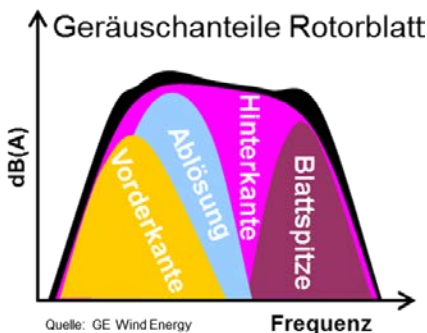


Figure 9: Perceived noise components of a wind rotor blade as a function of the frequency (yellow: leading edge; blue: flow separation; pink: trailing edge; purple: blade tip) [8]

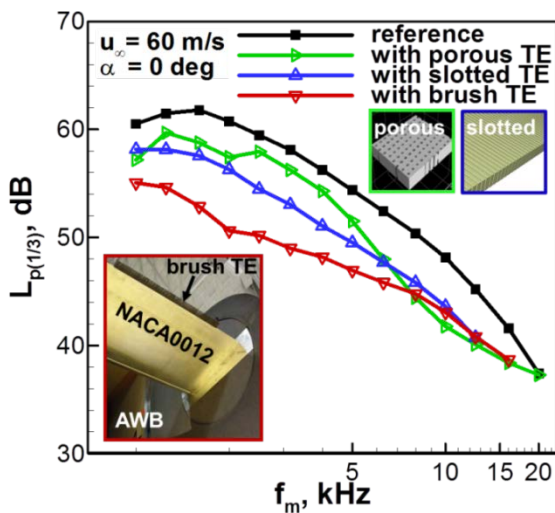
The study showed that the most promising control combination is a combination of individual pitch, active only at 1P, and trailing edge flap control, active at 2P. With this control setup 22% of life time damage equivalent load reduction is achieved at the flapwise blade root bending moment [7].

Focusing on the advantages of active blade components, such as flaps, rising problems, such as their acoustic behavior, must be taken into account. Through the additional moving parts and the associated gaps between the flap and the main blade structure, the flap itself becomes a new source of noise by itself. As it can be seen in Figure 9, one of the main noise sources on a wind turbine blade is the trailing edge. Using a flap mechanism at the trailing edge can therefore have a considerable

influence on the perceived noise level produced by the rotor blades.

In various activities, e.g. within the frame of the BELARWEA project, approaches are being investigated for reducing eventual annoyance effects, such as increments on noise emission levels, with the help of different trailing edge concepts. Amongst others it was shown that some tested trailing edge modifications could achieve a broadband noise reduction of up to 4 dB (Figure 10), depending on the used configuration [8]. The presented example shows four studied configurations schemes accounting for:

1. Continuous matching of the edge boundary conditions to free air ('impedance adjustment')
2. Geometric breakup of the solid edge contour
3. Hydrodynamic absorption and/or spectral reorganization of the incoming boundary-layer turbulence/flap side-edge vortex system before it passes the edge
4. Acoustic absorption



Along with the perceived noise level performance of the trailing edge modifications, it was shown that the noise reduction effect diminishes with growing angle-of attack and that pressure distribution measurements reveal a non-measurable to small effect of the trailing edge modifications on the airfoil's suction peak [9].

These fundamental results for the acoustic behavior of trailing edges without flaps need to be transferred to the smart blades with flaps concept.

Figure 10: Direct comparison of normalized trailing edge noise spectra for the studied concepts [9]

Leading Edge Slats

The third technology of the SmartBlades project deals with the impact of leading edge slats on the aerodynamic behavior of 2D profiles and of rotor blades under turbulent inflow conditions. The objectives of the research being to design an integrated leading edge slat concept; to perform wind tunnel tests on airfoils with active slats; and, finally, to study and proof the feasibility of the adaptive slat concept.

As a passive device, the slat shifts the angle of attack for reaching a maximum lift at even higher values, thus reducing the possibility of occurrence of flow separation. As an adaptive active device, the slat regulates the gap between the profile and the slat, affecting the flow around the profile and resulting in a different lift and drag behavior, allowing mitigating fluctuations in the acting forces. As an application case, the active as well as the passive slat applied along the span of the rotor blade of a wind turbine can help to achieve an optimized load distribution over the blade. Figure 11 illustrates the working principle of one of the developed concept configurations. The shape-adaptive slat is mounted in front of the main profile and the kinematic system is connected to the slat's trailing edge and borne in the front section [6].

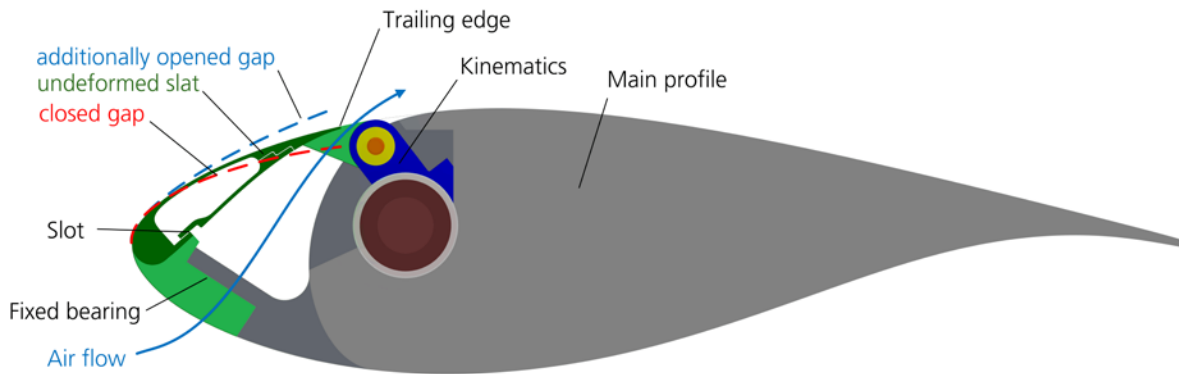


Figure 11: Working principle of the shape-adaptive slat with sketched deformed slat shapes [6]

During the SmartBlades project the slat concepts were proved to alleviate forces under turbulent flow conditions and to react to the fluctuating inflow. An example of the compensation that can be achieved with the slat system can be seen in the aerodynamic polars on Figure 12 [10].

In order to systematically characterize the behavior of the different slat concepts, it is necessary to study them in detail in turbulent wind tunnel tests.

It is expected that the active slat will offer more control capabilities than the other slat concepts. Therefore, results from detailed characterization in the wind tunnel could later serve as reference for various configurations.

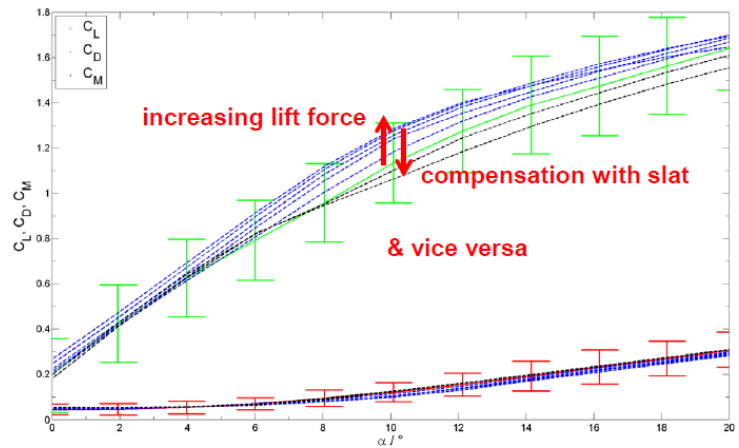


Figure 12: Averaged polars for the integrated slat at fixed positions in turbulent conditions ($Re \approx 600,000$, $\sin 5\text{Hz}$, $\pm 6^\circ \text{AoA}$) [10]

Smart Blades Evaluation

The described SmartBlades technology developments have proved the potential for reducing structural loads, enabling the building of larger rotors while remaining light, reducing noise levels and increasing power production. Remaining open points, such as a potential assessment of the new structures to be manufactured without a need for higher investments (and the directly related increment in costs) or of achieving a level of performance high enough to be worth the complexity of the new system, need to be further studied during follow up activities, e.g. in the SmartBlades2 project.

4. Validation and Verification

In order to be able to qualify the developed technologies, to guarantee a higher technology readiness level (TRL) and guide their entrance for implementation in industrial applications, it is necessary to verify and validate them first. Through analysis and simulation it is nowadays possible to achieve detailed knowledge on the function and characteristics of a system and predict its behavior before even prototypes have been built, all with high levels of confidence. Furthermore, thanks to current software, the obtaining of data describing the behavior of the system in detail, covering multidisciplinary aspects, such as structural and aerodynamic behavior

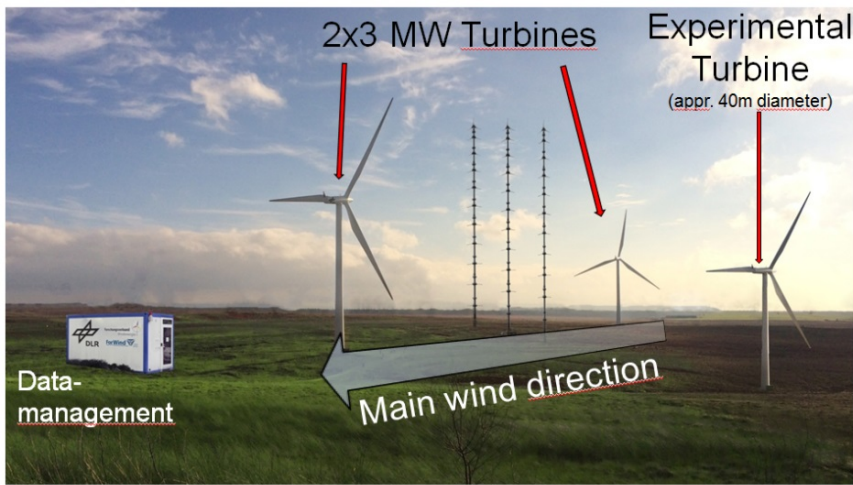


Figure 13: Platform for Wind Energy Research concept

or control engineering, while providing multi-fidelity results, is also possible. Independently of how high the level of confidence on the simulation models is, it is still necessary to test them on field to be able to ensure their efficiency and robustness under real (and possible) operating conditions; and, to experimentally prove further factors relevant to their acceptance, such as noise emission levels, which can only be proven under real environment testing conditions.

For this, it is necessary to have a real environment testing platform capable of measuring the behavior of the system, still at a demonstrator level, but under realistic conditions. This would allow to know real possible reactions of the structure and its components and to obtain real time accurate data regarding its behavior. The only possible way to qualify the structure, achieve a higher TRL and take the next step towards an introduction into industrial applications, is by obtaining this information.

5. Wind Energy Research Platform

A step towards creating a wind energy research platform capable of offering adequate data collection and testing possibilities is currently undertaken in the project ProWind (Platform for Research on Wind Energy) in Lower Saxony by planning and implementing a basic research infrastructure comprising of two ~2,5 MW-class research turbines [11].

In addition, the DFWind project (Deutsche Forschungsplattform für Windenergie – German Research Platform for Wind Energy) [12], aims to further develop the research platform by comprehensively instrumenting the research turbines and the surrounding site, in order to be capable of providing a basis for holistic wind energy research.

It is planned to obtain basic turbine data and monitor it with the help of condition monitoring systems (CMS) on the turbine itself. The ensemble shall also provide the capabilities for taking meteorological and acoustics measurements, evaluating the structure, analyzing the aerodynamics at the rotor blades and offering the necessary support structure and geotechnical information. As a result, the platform can supply the capacity for understanding the whole turbine system dynamics in a detailed manner. Figure 14 presents a simplified

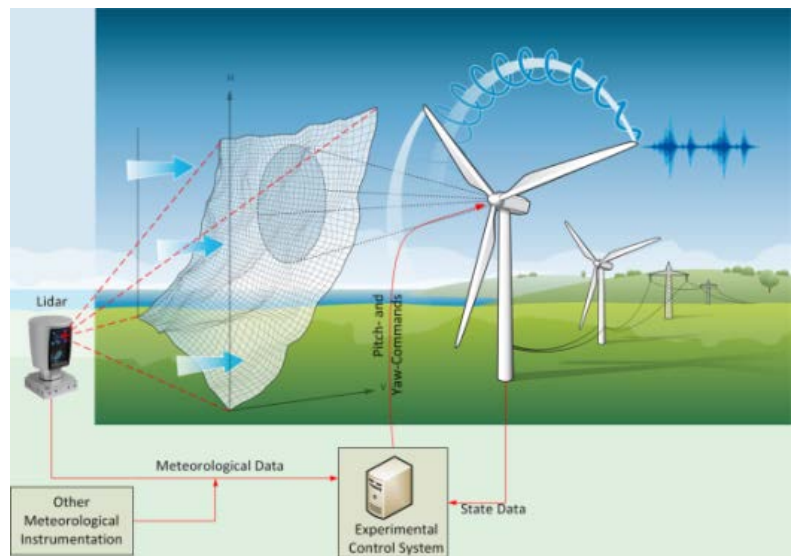


Figure 14: DFWind Experimental Turbine Concept [12]

view of the concept.

The main characteristics of the platform making it unique on its kind are the following [11]:

- Two identical, highly instrumented, modified research turbines of the current multi-MW class (of approximately 2.5 MW) available
- Experimental plant control on at least one of these turbines possible
- Measurements of wind fields, gusts and turbulence fields, including the wake trailing behind the turbine
- Multidisciplinary rotor blade research, structure monitoring, power output and aerodynamics measurements of the wind turbines
- Instrumentation of blades, drive train and support structure for recording the overall dynamics, development of whole system models for defining the interactions between all turbine components
- Global monitoring of the support structure and continuous measurements on stress-critical locations and connections in the context of long-term monitoring
- Integrated view of the wind turbine noise, from the emission to the transport to the immission
- Interaction of electromagnetic fields with operating parameters of the system, creation of mass, shielding and lightning protection concepts

This research platform will allow investigating numerous topics covering the entire wind energy system functional chain with high quality and detail, as well as focusing on the interaction of the subsystems and studying their influence not only on the overall wind turbine system, but also on the two separate wind turbines network.

6. Summary and Conclusions

This paper presented an overview of the status of current research on innovative rotor blade approaches for wind turbines. It was shown that according to current trends, wind turbines are still getting larger to be able to satisfy the market demands; however, building larger rotor blades presents several challenges related to costs and acceptance but also to technical aspects, such as structural capacity. Projects such as SmartBlades with its three investigated technologies (bending-twist coupling blades, flaps and slats) show potential for redesigning wind turbine blades to be able to fulfill the technical challenges, but, in order to introduce these new technologies to the industry and reach a sufficient TRL, further research, further development and tests, and finally, full scale validation through testing platforms, such as the planned DFWind platform, are necessary.

Acknowledgements

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