Publishable Summary for 19ENG08 WindEFCY
Traceable mechanical and electrical power measurement for efficiency determination of wind turbines

Overview

Wind energy has much potential to tackle climate change, but the efficiency of wind turbines must be improved. The overall aim of this project was to establish a reliable, practical, and traceable efficiency determination method for nacelles on large-scale test benches, enabling the wind energy sector to enhance the efficiency of wind turbine drive trains through comparable, repeatable testing. Achieving this objective empowers industry professionals with more precise and standardised efficiency assessments, facilitating quicker development cycles and streamlined time-to-market strategies for improved wind turbine drive train efficiency. The project's outcomes, including three comprehensive Good Practice Guides, provide practical solutions for traceable mechanical and electrical power measurements, further advancing efficiency assessments and supporting accelerated development cycles in the wind energy sector.

Need

The EU aims to become number one in the use of renewables, thus accelerating the energy transition towards cleaner energy sources. In 2017, the renewable with the highest capacity installations was wind power with 15.6 GW, a share of 65.3 % of all renewable power installations. To keep its top position in renewables, future wind turbines must be highly innovative, have reduced cost and improved performance. There was a clear need to quicken the development cycles, shorten the time to market of innovations and reduce the cost of mainstream technologies in the wind energy sector. Cost reduction already started by installing test benches for nacelles and their components, but to further reduce it and ensure resilience, security and high reliability of the power production, the development and testing process needed further improvements.

Standardised test and validation methods are important for quality assurance. However, so far, there were no standardised tests for the efficiency determination of nacelles (the wind turbine drive train, the gearbox if available, the generator) and their single components (such as generator, transformer and filters) on test benches. There was a clear need to develop traceable methods for reliable efficiency determination for nacelles prior to their installation in the field. This included traceable mechanical and electrical power measurement in nacelle test benches.

Objectives

The overall aim of the project was to support the European energy transition towards renewable energy sources in form of wind turbines by providing a traceable efficiency determination method for devices under test on nacelle test benches and, therefore, to shorten their time to market and to ameliorate their performance.

The specific objectives of the project were:

1. To carry out detailed assessment of available power and efficiency determination methods and measurements including all boundary conditions. This included the evaluation of power curve measurements both in the field and in test benches, and comparison of direct and indirect efficiency determination where the ratio of output to input and the power dissipation were calculated respectively.
2. To develop a good practice guide on traceable measurement methods with a target uncertainty below 0.5 % for mechanical power based on torque measurements up to 5 MN m with synchronised measurements of rotational speed up to 20 min^{-1} on the low-speed shaft respectively torque measurements up to 100 kN m with synchronised measurements of rotational speed up to 1600 min^{-1} on the high-speed shaft.

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3. To develop a good practice guide on traceable measurement methods for electrical power components from the generator, the converter and the filter, which suppress harmonics.
4. To develop a good practice guide on traceable methods for the efficiency determination of devices on test benches with a target uncertainty of 1 % by combining and synchronising the mechanical and electrical power measurements including an uncertainty model. Standardised guidelines for traceable efficiency determination on test benches were developed.
5. To facilitate the take up of the technology and measurement infrastructure developed in the project by the measurement supply chain, standards developing organisations (IEC TC88) and end users (wind turbine manufacturers, wind park planners, test bench operators).

Progress beyond the state of the art

Objective 1: To carry out detailed assessment of available power and efficiency determination methods.

Test benches offer the advantage of recording a wide range of various data in a short period of time. However, current approaches to determine the efficiency of nacelles on test benches such as the calorimetric and alternative back-to-back method, lack either the time advantage or the traceability. This project went beyond the state of the art by assessing available power and efficiency determination methods and their boundary conditions in detail in order to build a base for the development of a new standardised efficiency determination method performed on test benches.

Objective 2: To develop a good practice guide on traceable measurement methods for mechanical power.

Test bench operations demand highly accurate torque and rotational speed measurements traced to national standards. As stated in EMPIR 14IND14 “Torque measurement in the MN m range”, traceable torque measurement above 1.1 MN m was challenging. Moreover, no transfer standard for mechanical power measurement existed. This project went beyond that by developing and implementing a traceable mechanical power measurement standard based on synchronised torque and rotational speed measurement on both the low-speed shaft and the high-speed shaft.

Objective 3: To develop a good practice guide on traceable measurement methods for electrical power.

For the efficiency determination of electrical components in nacelles, such as the transformer, converter and harmonic filter, electrical power measurements under non-sinusoidal conditions at high voltage must be carried out. Commercial systems to measure electrical power need to be traced to national standards. So far, traceable in-field calibrations under realistic conditions, i.e., distorted voltage and current waveforms with amplitudes of some 10 kV and some kiloamperes were not available. This project went beyond that by developing and implementing a traceable measurement method for electrical power components.

Objective 4: To develop a good practice guide on traceable methods for the efficiency determination of devices on test benches.

Currently, wind turbines are classified by their power performance, which is measured in the field according to IEC 61400-12-1. This uniform methodology ensures the development and operation of wind turbines including a consistent, accurate and reproducible determination of wind turbine power performance. It represented the average power generated as a function of the mean values of wind speed at hub height. However, this method was very time-consuming and highly affected by the variability of wind conditions. In addition, the power curve did not allow any conclusions to be drawn about the drive train efficiency. This project went beyond the state-of-the-art and reduced this measurement timeframe by providing the wind community with a standardised method for efficiency determination of nacelles on test benches.

Results

Objective 1: To carry out detailed assessment of available power and efficiency determination methods.

A detailed study presenting the state-of-the-art for determining the efficiency of wind turbines in the field including a description of relevant standards such as IEC 61400-12-1, the MEASNET guideline “Power Performance Measurement Procedure” and the FGW guideline TR2 has been created. The report served as the basis for all other objectives as it provided information on the efficiency determination in different aspects and on synchronisation technologies for different data acquisition systems. The objective has been successfully achieved through a comprehensive assessment, analysis, and development of new efficiency determination methods for wind turbine drivetrains.

Objective 2: To develop a good practice guide on traceable measurement methods for mechanical power.

A 5 MN m torque transducer was calibrated up to 1.1 MN m performed on the Torque Standard Machine at PTB and using the linear regression model, the uncertainty coverage corridor was estimated at 0.055%–0.065%. The total expanded uncertainty of torque measurements in single points was estimated at the level of 0.08%. The torque transducer was developed as the torque transfer standard by using a newly extrapolation method which was developed based on partial calibrations. The expanded uncertainty of torque measurement on the 4MW NTB at CWD of RWTH Aachen University at selected points (static and dynamic) in the range of up to 1.5 MN m was estimated at 0.29%, and in the range from 1.5 MN m to 5 MN m it was estimated at 0.53%.

In accordance with requirement specifications for rotational speed measurement in nacelle test benches, a suitable stator-less tachometer in form of two inclinometers was chosen and procured. The inclinometers measured the rotational angle over time to determine the average rotational speed. A calibration procedure for tachometers measuring rotational speed was developed and applied to the inclinometers. The transfer standard for mechanical power measurement, consisting of the 5 MN m torque transducer and the inclinometer for rotational speed measurement, was utilised to perform calibration measurements in the 10 MW nacelle system test bench DyNaLab at Fraunhofer IWES, Germany, and in the 4 MW nacelle system test bench at the Center for Wind Power Drives (CWD) at RWTH Aachen University, Germany.

In the DyNaLab, the relative indication deviation of the torque measurement was -4.0 %, and the expanded relative measurement uncertainty for the calibrated rotational speed measurement was 0.032 % at maximum rotational speed. At CWD, the test bench's own transducer measured torque with a relative indication deviation of about +4.2 % and the expanded relative measurement uncertainty for the rotational speed calibration was 0.025 %. Utilising the evaluated calibration results, a second measurement campaign at CWD with a different Device Under Test (DUT) concept was successfully executed to measure mechanical power with traceable uncertainty estimation without relying on the transfer standards.

Moreover, a new torque transducer for torque measurement under rotation was calibrated statically and mounted in the 200 kW small-scale motor test bench. Discrepancies between the signal readout during static calibration and that measured in the motor test bench by a power analyser were observed. In case the power analyser used a short averaging time, the torque transducer's accuracy was significantly lower than stated during the static calibration. If the averaging time could not be prolonged and thereby the torque ripples reduced to a negligible minimum, the remaining torque deviation must be considered as uncertainty contribution for torque measurement under rotation. To gain a better understanding of torque measurement at high rotational speeds, a Finite Element Method (FEM) model of the torque transducer was developed, and analysis were conducted to investigate torque measurement under rotation. The results revealed a deviation up to 0.01 % at 3000 min^{-1} using only one strain gauge bridge. The deviation was a result of strain gauge positioning misalignment and was related to the rotational speed. However, by implementing multiple strain gauges and using active compensation, the torque deviation under rotation could be minimised.

As torque measurements in test benches were not performed statically, analyses on continuous and randomised calibration loads were undertaken. In doing so, the susceptibility of transducers to conditions (creep and hysteresis) and load profiles prior to the desired measurement plateau (previous load step) was shown. Both standardised and non-standardised calibrations of multiple torque transducers were documented in a project output. The in-situ calibration procedure for traceable mechanical power measurement using the developed transfer standards can be found in the, produced by the project, Good Practice Guide for mechanical power determination.

The objective has been successfully achieved by developing a comprehensive Good Practice Guide, advancing traceable measurement methods for mechanical power with practical solutions in torque and rotational speed. The achieved results contribute significantly to enhancing reliability in mechanical input determinations on nacelle test benches, aligning with the targeted uncertainty below 0.5%.

Objective 3: To develop a good practice guide on traceable measurement methods for electrical power.

To calibrate electrical power components, a reference power measurement system was established. It was composed of a power analyser, precision wideband high voltage dividers, and precision current transducers with build-in electronics. The calibration system for the power analyser was set up. A reference voltage divider was designed for calibrating the voltage transformers, and current transformers were purchased and calibrated for current measurement. The reference power measurement system was used to conduct calibration measurements at DyNaLab at Fraunhofer IWES, and in the 4 MW nacelle system test bench at the CWD at RWTH Aachen University. As *in-situ* calibration of the voltage dividers at DyNaLab was not possible, they were externally calibrated using the reference voltage divider designed within the project. Besides linearity and frequency response measurements, the translation measurement deviations and phase displacement were determined. Additionally, the influence of receivers and transmitters, burden and channel dependency of the receiver and the transmitter dependency were analysed.

A software called "TorqueWind" was developed to calculate the air gap torque in the generator. The calculations were based on precise information about the machine type and the measured electrical quantities of current and voltage. Test results of a 60 kW machine in a motor test bench showed the influence of the inverter on the air gap torque. To validate the software, the input torque was measured using a commercial torque transducer.

With the assistance of the newly constructed reference power measurement system, future electrical power measurements in test benches could be calibrated following the good practice guide. The produced Good Practice Guide for traceable electrical power measurement was based on the performed examinations. The measurements carried out in the test benches served as a proof of concept of the measurement method and initial calibration of electrical power measurements in the respective test benches. The objective has been successfully achieved through the development and implementation of this comprehensive Good Practice Guide, bridging the theoretical concept of traceable measurement methods for electrical power components to practical solutions in nacelle test benches.

Objective 4: To develop a good practice guide on traceable methods for the efficiency determination of devices on test benches.

A practical and traceable measurement procedure for the determination of nacelle efficiency on test benches was developed. The procedure was tested on several motor, generator, and nacelle test benches, including the 200 kW motor test bench at PTB, Germany; the 10 MW nacelle test bench and the generator test bench HiL-GridCoP both at Fraunhofer IWES, Germany; the 4 MW nacelle test bench at CWD, Germany. The procedure was based on EN 60034-2-1 and was extended for additional working points, which combined torque and rotational speed. To verify this newly developed measurement procedure, an existing 200 kW motor test bench was modified to resemble the set-up of nacelle test benches and extended by an additional torque transducer measuring in line with the existing torque transducer.

On the 4 MW CWD test bench, the efficiency of a 2.75 MW nacelle drive train was determined using the transfer standards for mechanical and electrical power measurement. The overall system efficiency was 89 % in the rated range, with a relative expanded measurement uncertainty of up to 0.72 %. Compared to using the uncalibrated measurement system, the efficiency was measured approximately 4 % higher. Factors like the measurement uncertainty of the static torque calibration, which significantly contributed to the overall measurement uncertainty, as well as influences such as torque ripples and load step instability were considered. With a relative expanded measurement uncertainty of 0.019 %, the uncertainty contribution of the reference power measurement system was negligible. The efficiency of drive trains was found to be very temperature-dependent, with variances exceeding the specified measurement uncertainty range for each load step. Consequently, this project proposed that a standardised efficiency determination procedure should not only be based on torque and rotational speed, but also on temperature.

In the second measurement campaign on the 4 MW CWD test bench, the configuration of the DUT was changed. Using the calibration results from the first measurement campaign, the efficiency of the new DUT concept was successfully determined with traceable uncertainty estimation and without installing the transfer standards. The overall system efficiency of the new DUT concept was 93 % in the rated range, with a relative expanded measurement uncertainty of up to 0.94 %.

In addition, a wind turbine was tested on the 10 MW nacelle test bench "DyNaLab" of Fraunhofer IWES in Bremerhaven Germany. During the test campaign, the 5 MN m torque transducer, as well as other mechanical and electrical sensors were adopted for traceable measurements of input and output powers. Efficiency behaviour of the turbine on numerous working points up to 5 MN m and under different conditions was determined. Addressing the challenge in the measurement accuracy, state-of-the-art sensors and measurement systems as well as calibration facilities were used. The results showed that an overall uncertainty level of 0.7% was achievable for the efficiency determination, with torque measurement up to 5 MN m. As expected, torque measurement contributed the largest part of the uncertainty. Surprisingly, the electrical power measurement was also contributed a large part to the uncertainty. This pointed out that electrical power measurement needed equal care like the mechanical power, although it was generally considered more accurate than the latter. The speed measurement based on the inclinometer has shown very good results. To achieve a stable efficiency, the measurement of at least six full revolutions was averaged, resulting in almost negligible contributions in the overall uncertainty. The objective has been successfully achieved. The developed Good Practice Guide for efficiency determination provides a standardised and traceable measurement method, which is both less time-consuming and reproducible. The guide is validated across multiple test benches and demonstrates its effectiveness in combining mechanical and electrical power measurements, providing traceable efficiency determinations with an overall uncertainty level of 0.7%

Impact

In the first half of the project, the measuring systems for mechanical and electrical power were established and characterised. Most of the results were published in the second half of the project. To keep the stakeholders and other interested parties updated and in touch with the consortium, two issues of the project's newsletter were disseminated. At the beginning of the project, two press releases regarding the project's research proposal were issued. Throughout the project's duration, news updates were shared on the social media platform Facebook, and various seminars in Poland, Spain and Germany featured project-related information. In the final stakeholder workshop, the project's outcomes attracted over 50 participances, with more than 35 of them coming from industries and universities outside of the project. A technical article was published at the Brazil Windpower 2021 event, organised by the Brazilian Wind Energy Association. Furthermore, the project objectives were presented at standardisation meetings of DKE K311, Euramet TC-M and DKD Fachausschuss "Kraft und Beschleunigung" (force and acceleration), and the project results were showcased at the EURAMET TC-M SC Force meeting in September 2023. Eight deliverable reports about the project's findings were made available on the project's website. Four publications appeared in peer-reviewed journals, and three publications were submitted for open access publication and are currently awaiting feedback. Seven peer-reviewed conference contributions were published. 25 publications in conference proceedings have been made so far and at least two more conference contributions were submitted in 2023. Also, the project website was updated regularly with the project's key achievements and planned activities. Lastly, a scientific employee from the Brazilian National Metrology Institute Inmetro spent five months at PTB for a scientific exchange.

Impact on industrial and other user communities

The Good Practice Guides provided by the project WindEFCY offered detailed, step-by-step instructions for traceable measurement procedures for mechanical and electrical power, as well as efficiency determination in nacelle test benches (Objectives 2 – 4). Following these guides, industrial communities, especially test bench operators, can have their measurement systems calibrated through in-situ calibration using transfer standards. After the calibration, operators are instructed on how to implement the calibration results and perform efficiency measurements with traceable uncertainty estimation for their customers.

Wind turbine manufacturers, gearbox manufacturers, test bench operators, and wind park planners/operators all benefited from the results of this project. A reproducible efficiency determination on test benches shortened the development cycles, reduced time to market in the wind energy sector, and strengthened the competitiveness of European wind turbine manufacturers. Reliable specifications with trustworthy proofs of compliance allowed wind park planners, operators, and the electricity grid to optimise their investments. While the project focused on traceable efficiency determination of nacelles and their components on test benches, other industrial sectors also benefited from the results. The procedures were adapted to other industries where mechanical energy was transformed into electrical energy and vice versa, such as the rail and marine transport sectors or the hydropower and gas power industry. Based on the project results, methods developed to test large gearboxes or bearings provided a more precise determination of efficiency losses, which were only estimated, and thus improved their quality. A procedure for efficiency determination in a much smaller power range supported the electrification of the automobile industry, including lorries and tractors, since the high rotational speed was a key parameter for eDrive applications.

Impact on the metrology and scientific communities

Within the project, calibration procedures for traceable mechanical and electrical power measurement were developed (Objective 2 & 3), and the associated required reference standards were established. This paved the way for new Calibration and Measurement Capabilities in the participating National Metrology Institutes. The scientific community, concerned with simulations, benefited from this project by improved validations of their simulation data through more precise, reliable, and trustworthy measurement results with lower uncertainty.

Impact on relevant standards

Official guidelines or standards for the efficiency determination of wind turbine drive trains and their components on test benches did not exist prior to this project, nor did regulations for mechanical power measurement. The project's results, especially those related to mechanical power measurement (Objective 2), will be input to the BIPM CCM Working Group on Force and Torque so that new regulations and standards can be developed. Testing on test benches gained an edge over field tests because they were time-saving and reproducible. The project introduced the results to IEC TC88 "Wind energy generation systems" to stimulate and support future standards. Furthermore, the guidelines on the efficiency determination and calibration of mechanical and electrical power measurement were available as free downloads on the project's website.

Longer-term economic, social and environmental impacts

The measurement campaigns conducted in two different test benches indicated significant deviations using uncalibrated measurement systems. Compared to the correct efficiency measured by the transfer standards, the test bench at DyNaLab measured a ca. +4% deviated efficiency, while the test bench at CWD measured a ca. -4% deviated efficiency. This highlighted the importance of providing traceability to the wind power industry. A major economic impact was the quality assurance and reliable comparability of drive train components and entire wind turbines through standardised methods for traceable efficiency determination. A reliable comparison of the efficiency of individual drive train components will lead to a quicker and more efficient development cycle, resulting to a shorter time-to-market. Moreover, a profit and loss account of a planned wind park can vary significantly for a determined efficiency of 95 % with a measurement uncertainty of 2 % of a wind turbine. For the world's biggest offshore wind park, Walney Extension in the UK with a maximum power of 659 MW, the energy corresponding to the uncertainty of the efficiency could power about 14 000 four-person households with an assumed energy consumption of 4000 kWh per year. A large uncertainty of the efficiency can, hence, lead to incorrect conclusions about the profitability of the planned wind park. Highly efficient products only become competitive when the uncertainty of the efficiency is sufficiently small.

List of publications

1. Mester. (2021). 'Sampling Primary Power Standard from DC up to 9 kHz Using Commercial Off-The-Shelf Components' https://dx.doi.org/10.3390/en14082203
2. Dubowik, Mohns, Mester, Heller, Zweiffel, Quintanilla Crespo, Hällström, Weidinger. (2021). 'Report on the technical requirements for the electrical power measurements and definition of the measurands for nacelle test benches' https://doi.org/10.5281/zenodo.4726089
3. Song, Weidinger, Eich, Zhang, Yogal, Kumme. (2021). '10 MW mechanical power transfer standard for nacelle test benches using a torque transducer and an inclinometer' https://dx.doi.org/10.1016/j.measen.2021.100249
4. Weidinger, Zweiffel, Dubowik, Eich, Lehrmann, Mester, Yogal, Zhang, Kumme. (2021). 'Need for a traceable efficiency determination method of nacelles performed on test benches' https://dx.doi.org/10.1016/j.measen.2021.100159

5. Yogal, Lehrmann, Song, Weidinger, Kumme, Oliveira. (2022). 'Efficiency measurement with a focus on the influence of rotation and temperature on torque measurements performed on small-scale test benches' https://doi.org/10.21014/tc3-2022.083
6. Oliveira, Weidinger, Song, Vavrečka, Fidelus, Kananen, Kilponen. (2022). 'Transducer response under non-standardised torque load profiles' https://doi.org/10.21014/tc3-2022.116
7. Zhang, Pieper, Heller. (2023). 'Direct measurement of input loads for the wind turbine drivetrain under test on a nacelle test bench' https://doi.org/10.1007/s10010-023-00628-z
8. Zweiffel, Jacobs, Song, Weidinger, Decker, Röder, Bosse. (2023). 'Influence of drivetrain efficiency determination on the torque control of wind turbines' https://doi.org/10.1007/s10010-023-00630-5
9. Song, Weidinger, Zweiffel, Dubowik, Mester, Yogal, Oliveira. (2023). 'Traceable efficiency determination of a 2.75 MW nacelle on a test bench' https://doi.org/10.1007/s10010-023-00650-1
10. Song, Weidinger, Zweiffel, Dubowik, Oliveira, Yogal, Mester. (2023). 'Importance of traceability of determining the efficiency of wind turbine drive trains on test benches' https://doi.org/10.5162/SMSI2023/P52
11. Weidinger, Song, Zhang, Zweiffel, Oliveira. (2023). 'Zero signal determination for torque measurement under rotation in test benches' https://doi.org/10.5162/SMSI2023/D4.2
12. Fidelus, Puchalski, Trych-Wildner, Urbañski, Weidinger. (2023). "Estimation of Uncertainty for the Torque Transducer in MNm Range—Classical Approach and Fuzzy Sets" https://doi.org/10.3390/en16166064

This list is also available here: https://www.euramet.org/repository/research-publications-repository-link/

Project start date and duration:	01 September 2020, 36 months	
Coordinator: Rolf Kumme, PTB Tel: +49 531 592 1200 E -mail: rolf.kumme@ptb.de Project website address: https://www.ptb.de/empir2020/windefcy/home/		
Internal Funded Partners: 1. PTB, Germany 2. CMI, Czech Republic 3. GUM, Poland 4. METAS, Switzerland 5. VTT, Finland	External Funded Partners: 6. CENER, Spain 7. DINNTECO, Spain 8. FhG, Germany 9. RWTH, Germany 10. THAB, Germany	Unfunded Partners: 11. Inmetro, Brazil
RMG: -		