FINAL PUBLISHABLE REPORT

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1 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.

2 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.

3 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.
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).

4 Results

4.1 Overview of existing power and efficiency determination methods for wind turbines

Objective 1: To carry out detailed assessment of available power and efficiency determination methods and measurements including all boundary conditions. This will also include 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 are calculated respectively.

Wind turbine efficiency determination methods in the field

The efficiency measurement of wind turbine drivetrains has not been a prioritized task in the past. Therefore, existing guidelines rely primarily on power curve measurements in the field. These guidelines, particularly IEC 61400-12-1, exhibit drawbacks by not specifically addressing the efficiency of the drivetrain. Moreover, the guidelines correlate the wind speed with the power production of the wind turbine by calculating a power coefficient and a power curve. However, these methods are implemented and compared to inform the development of test bench methodologies.

RWTH as a task coordinator with the support of other partners (CENER, FhG, Inmetro, DINNTECO, METAS, PTB and VTT) has done literature research on the efficiency determination of wind turbines in the field. Various guidelines, such as MEASNET and FGW, complementing IEC 61400-12-1 for wind turbine certification were reviewed. Their methods undergo evaluation for accuracy, repeatability, and traceability, aligning with IEC criteria covering electrical power measurement, wind speed measurement, and data processing.

Transitioning to efficiency measurement on test benches offers insights into power measurement accuracies. Unlike field tests with uncontrollable wind speeds, test benches provide reproducible conditions, enhancing measurement accuracy. Controllable parameters such as speed or torque at the rotor hub eliminate uncertainties related to wind speed measurements.

In a stable test bench setting, ambient measurements become crucial, ensuring controlled parameters for both the specimen and measurement equipment, minimizing external influences. This stability reduces the need for time-consuming and long period averaging, typical in field test requirements.

Moreover, test bench environments eliminate concerns related to data rejection due to icing or contamination events. Stable conditions enable a higher sampling frequency of the measurement system, anticipating variations in specimen behaviour.

Factors like air density, significant in field tests, become negligible in test bench scenarios. Differences in average site density and standard density do not significantly contribute to uncertainty. In summary, transitioning from field to test bench evaluations enhances accuracy and efficiency in wind turbine drivetrain assessments.

Efficiency measurement methods performed in test benches.

Test benches play a pivotal role in expediting time-to-market for innovations and reducing development costs. In contrast to time-consuming and non-reproducible in-field measurements, test bench measurements offer a promising alternative. The state-of-the-art efficiency measurement methods on nacelle test benches, focusing on the "calorimetric efficiency" method and an alternative back-to-back efficiency determination method, are described and evaluated.

The calorimetric efficiency measurement, as demonstrated in the HybridDrive project at RWTH, involves assessing an integrated drivetrain with a two-stage planetary gearbox and a 3 MW permanent magnet mid-speed synchronous generator. This method relies on measuring heat losses in the drivetrain, resulting in significantly higher accuracy at high efficiencies. The resulting uncertainties of the measurements below 0.5 %

show that this method is feasible for efficiency determination. However, the method is time-consuming due to the need for equilibrium temperatures and the impracticability for isolating an entire multi-megawatt nacelle. The isolation's imperfection introduces measurement errors that cannot be quantified with sufficient accuracy.

The alternative back-to-back efficiency determination method addresses the limitations of common input torque measurement in wind turbine drivetrains. Instead of directly measuring efficiency, this method concentrates on power loss measurement to enhance accuracy. It requires a specially designed test procedure involving operation in generator mode (Test A) and motor mode (Test B) to compare mechanical and electrical power measurements and determine power loss for a specific operating point. The proposed Alternative back-to-back test method for efficiency determination allows for measuring the drivetrain efficiency of wind turbines with high accuracy, without high accuracies on electrical and mechanical power measurements. The uncertainty of the measured drivetrain efficiency is lower than 1 %, while a decrease to under 0.5 % is considered possible in the future.

Comparing these methods, they both achieve a satisfying accuracy of under 0.5 %. However, a notable limitation is that efficiency measurements can only be performed for single operation points, making the procedures time-consuming and costly. Achieving a consistent temperature in every operation point adds to the complexity. Additionally, defining uncertainties and ensuring traceability to national standards are challenges faced by the existing methods. In their current form, these methods do not fully meet the demands of efficiency measurement on test benches. Further development and validation are essential to address the identified shortcomings and enhance the applicability of these methods in test bench environments.

Analysis of direct and indirect efficiency determination methods compared to IEC 60034

PTB, METAS and VTT assessed relevant standards for determining the efficiency of rotating electrical machines. The efficiency determination of electrical machines follows standards such as DIN EN 60034 and the international standard IEC 60034-2-1. These standards provide test methods for evaluating losses and efficiency classification, covering induction motors, synchronous machines, and DC machines. The efficiency classification (IE-Code) for AC motors is specified in IEC 60034-30-1.

The guideline created by PTB, THAB and VTT allows both methods (direct and indirect efficiency determination), each with its set of advantages and drawbacks. This analysis seeks to identify the current possibilities and limitations, forming the basis for developing the intended efficiency method and its associated project measurement setup. The assessment primarily focuses on the accuracy and traceability of these methods.

In the direct method, the efficiency of induction motors is calculated by comparing the measured output power to the input power, involving determining mechanical output power through overall rotational speed and mechanical torque measurement. Electrical input power is measured using high-precision power analysers, considering voltage, current, and power factor. However, small uncertainties and offset errors in torque measurement significantly impact power loss and measured efficiency due to the high efficiency of modern electrical machines.

The indirect method involves subtracting all machine losses from the electrical input power to determine mechanical output power. This approach eliminates constant offset errors in torque measurement, reducing the overall measurement uncertainty in calculated efficiency. The indirect method is recommended for induction motors in the IEC 60034 standard, except for single-phase motors, where the effect becomes more pronounced with increasing rated motor power.

For Permanent Magnet Synchronous Motors (PMSM), the standard does not specify an indirect method in addition to direct efficiency measurement. An alternative method to direct efficiency measurement exists for electrically excited synchronous machines but is not applicable to PMSMs due to physical constraints. For instance, determining friction losses in PMSMs requires a non-magnetized rotor, leading to increased measurement effort and complexity. While indirect efficiency measurement is more accurate for asynchronous or synchronous machines, the method is not feasible for the general efficiency determination guideline in Wind Turbine (WT) drivetrains, as Permanent Magnet Synchronous Generators (PMSG) used in the wind industry would be excluded. RWTH coordinated the input of all partners in WP and compiled it all in one consistent summary report. All partners involved in achieving Objective 1 (RWTH, CENER, CMI, DINNTECO, FhG, GUM, Inmetro, METAS, PTB, THAB and VTT) gave their feedback and sent it to RWTH. PTB submitted the summary report as deliverable D1: *'Document describing current state-of-the-art developments on efficiency determination methods for wind turbines and nacelles in the field and on test benches respectively, their traceability, and general methods for direct and indirect efficiency determination'* to the MSU.

Challenges for designing an efficiency determination method for nacelles on Nacelle Test Benches (NTB)s

Based on gathered knowledge from efficiency determination methods applied at RWTH, FhG, and CENER recommendations are provided for the development of a traceable measurement procedure, guidelines for calibrating mechanical and electrical power measurement, and a good practice guide for the efficiency determination of devices on test benches:

- For reliable efficiency determination, traced mechanical and electrical power measurement is required, along with appropriate synchronization.
- A suitable transfer standard is required for torque measurement in test benches due to parasitic loads caused by misalignments and, in the case of system NTBs, an active control system.
- Due to electromagnetic fields and environmental conditions influencing electrical power measurement, it should also be calibrated in the field using a reference power measurement system.
- The indirect efficiency determination method, including the segregation of loss method with linked temperature corrections, cannot be applied to all nacelles in test benches, leading to high accuracy of mechanical power measurement using the direct efficiency determination method. Wind turbines operate at variable speed, requiring efficiency determination at different load points through efficiency maps or iso efficiency contours.

The results are described in more detail in deliverable D1 of the project, mentioned above.

Summary

In alignment with Objective 1 – the assessment of existing power curve methods and efficiency determination techniques on test benches – this project has uncovered a noticeable absence of standardised and easily reproducible efficiency determination techniques for nacelles. These methods lack traceability and practical applicability in measurements. The analysis and comparison of direct and indirect methods for determining the efficiency of rotating electrical machines have led to recommendations for developing a new, comprehensive efficiency determination method for devices on test benches. Based on the accomplished objective, the project successfully devised a new standardised efficiency determination method for nacelles and their components on test benches. Simultaneously, transfer standards were developed for calibrating both mechanical and electrical power measurements. The new efficiency determination method, relying on calibrated and synchronized mechanical and electrical power measurements, was then implemented in two test benches associated with the WindEFCY project: the Dynamic Nacelle Testing Laboratory (DyNaLab) at Fraunhofer IWES in Bremerhaven, Germany, and the Center for Wind Power Drives (CWD) at RWTH Aachen University, Germany.

The objective has been successfully achieved through a comprehensive assessment, analysis, and development of new efficiency determination methods for wind turbine drivetrains Traceable mechanical power measurement.

4.2 Traceable mechanical power measurement

Objective 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.

Test bench operations demand highly accurate torque and rotational speed measurements that can be traced back to national standards. As stated in EMPIR 14IND14 "Torque measurement in the MN m range", traceable torque measurement above 1.1 MN m is 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.

These practical solutions consist of:

- Traceable torque measurement under rotation,
- Traceable rotational speed measurement,
- And traceable mechanical power determination.

Traceable torque measurement under rotation

A 5 MN m torque transducer had been calibrated up to 1.1 MN m, establishing it as a torque transfer standard (TTS). A new extrapolation method was developed by PTB, INMETRO, and GUM based on partial calibrations (GUM has determined and estimated the uncertainty coverage corridor at level (0.055–0.065) % using the linear regression method on the torque transducer up to 1.1 MN m based on measurement points with an expanded uncertainty of torque measurements in single points at the level of 0.08%.). This method utilized scaling factors, weighting factors of the transducer, and various prediction factors to determine the extrapolated relative expanded measurement uncertainty at 5 MN m, which was found to be 0.53 %. The achieved uncertainty of the transfer standard narrowly missed the targeted threshold of less than 0.5 %. To attain the desired goal of less than 0.5 % uncertainty for torques up to 5 MN m in mechanical power measurements, it is imperative to establish a direct traceability link to PTB's newly developed 5 MN m torque standard machine. This direct traceability is anticipated to yield a lower uncertainty for the transfer standard compared to the extrapolation method employed.

The 5 MN m torque transfer standard was utilized to perform calibration measurements in the 4 MW nacelle system test bench (Figure 1) at the Center for Wind Power Drives (CWD) at RWTH Aachen University, Germany, and in the 10 MW nacelle system test bench DyNaLab (Figure 2) at Fraunhofer IWES, Germany.

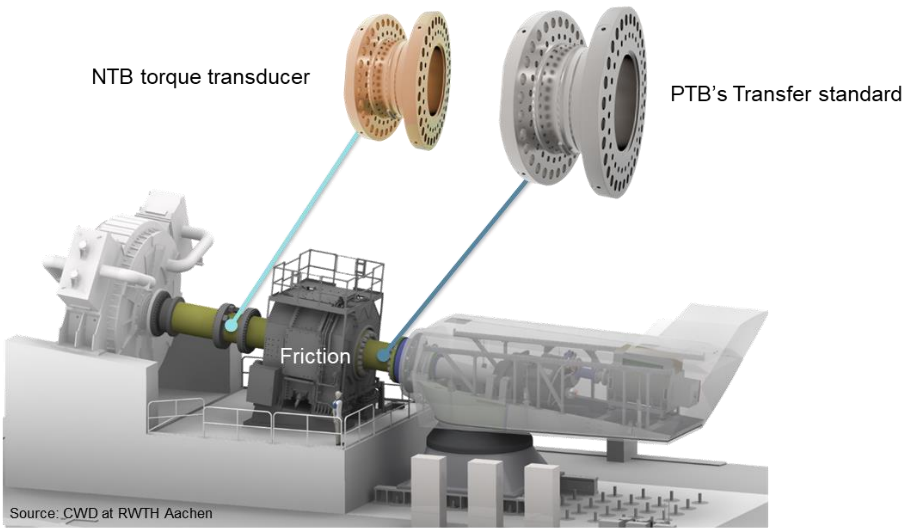

Figure 1 The 5 MN m torque transfer standard mounted in the CWD NTB

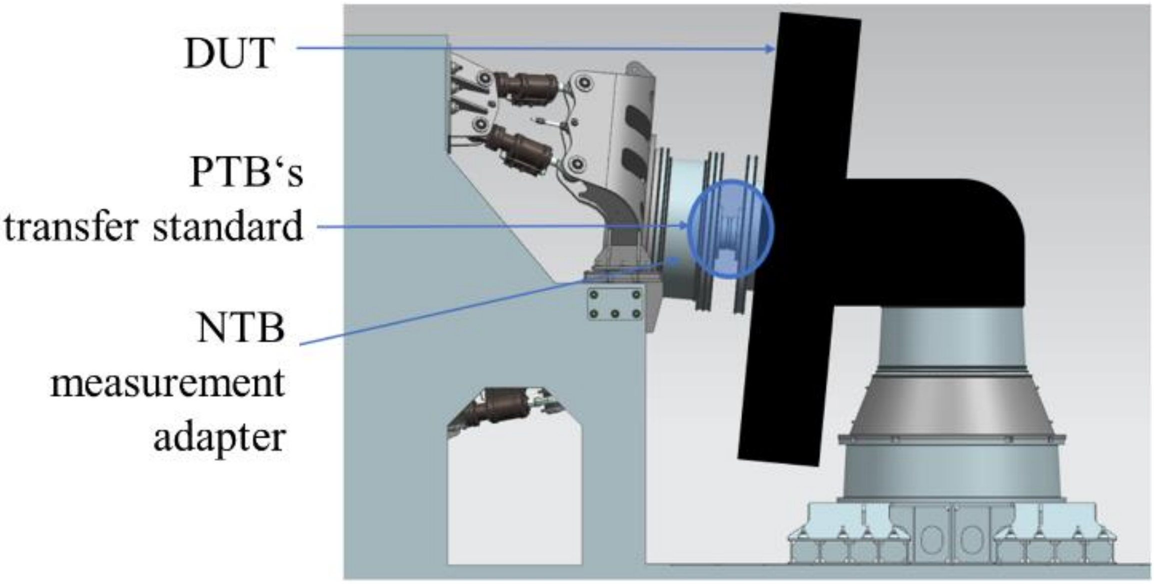

Figure 2 The 5 MN m torque transfer standard mounted in the DyNaLab NTB

In DyNaLab, the relative indication deviation of the torque measurement was -4.0 %. At CWD, the test bench's own transducer measured torque with a relative indication deviation of about +4.2 %. The significant differences highlight the great importance of providing traceability to the torque measurement on the NTBs.

Moreover, a new torque transducer for torque measurement under rotation has been calibrated statically and mounted in the 200 kW small-scale motor test bench at PTB. 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 uses a short averaging time, the torque transducer's accuracy is significantly lower than stated during the static calibration. If the averaging time cannot be prolonged and thereby the torque ripples reduced to a negligible minimum, the remaining torque deviation must be considered as an uncertainty contribution for torque measurement under rotation.

To gain a better understanding of torque measurement at high rotational speeds, CMI, GUM, Inmetro, and PTB performed theoretical calculations on the influence of rotational speed on the torque measurement. In addition, two Finite Element Method (FEM) models of the torque transducers were developed by PTB and Fraunhofer, 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 are not performed statically, analyses on continuous and randomised calibration loads were undertaken. The susceptibility of transducers to conditions (creep and hysteresis) and load profiles prior to the desired measurement plateau (previous load step) were shown. Both standardised and non-standardised calibrations of multiple torque transducers are documented in deliverable D3: '*Report describing the calibration of the 5 MN m torque transfer standard partially up to 1.1 MN m with an uncertainty < 0.1 % and in the full range up to 5 MN m with an uncertainty < 0.5 % 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*'.

Traceable rotational speed measurement

Based on an overview of encoders deployed in test benches executed by CMI and GUM, and a questionnaire that was answered by five stakeholders and three test bench operators, PTB, FhG, and RWTH defined the requirements for a tachometer for a traceable measurement of rotational speed up to 1600 min^{-1}.

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. It was calibrated using the calibration procedure developed by PTB, CMI, GUM, and VTT in cooperation with another department at PTB. This static calibration of the inclinometer shows an expanded measurement uncertainty (k = 2) of 0.014° and a repeatability of 0.005°. The inclinometer is developed as a transfer standard for rotational speed and combined with the 5 MN m TTS (Figure 3) and implemented on the NTB to establish a traceability chain of rotational speed measurement.

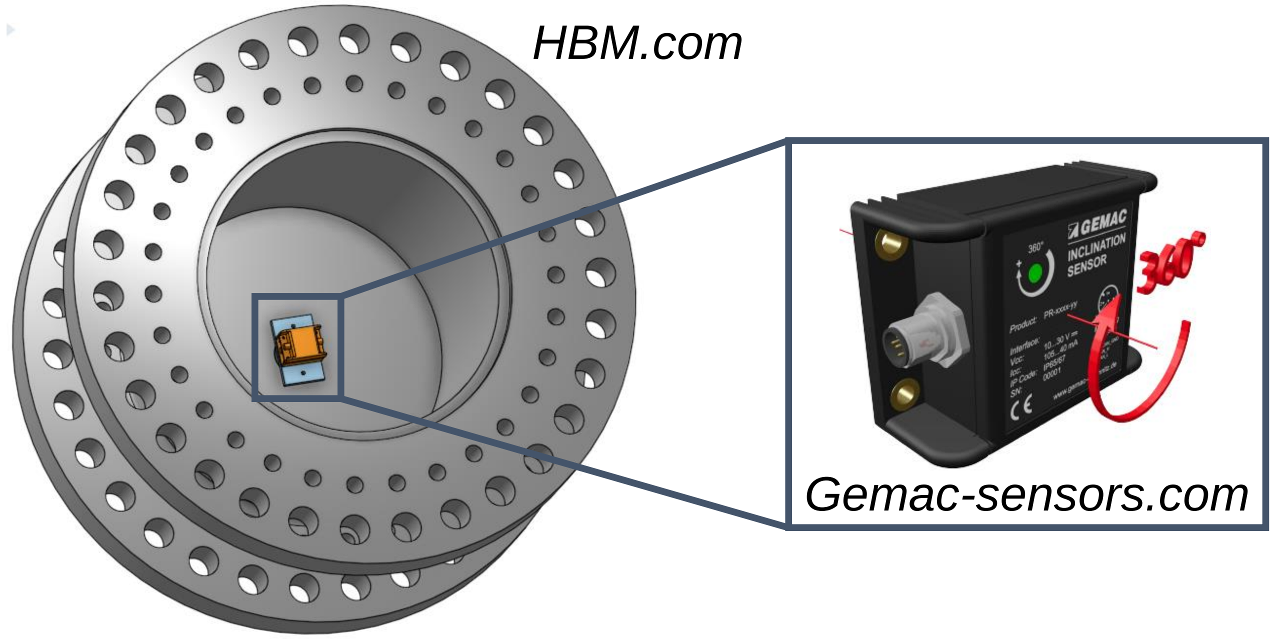

Figure 3: The transfer standard for mechanical power measurement consisting of a 5 MN m TTS and an inclinometer used in the project to calibrate mechanical power measurement in NTBs as an example.

On the NTB, additional measurement uncertainty contributed by to mounting misalignments, eccentricity, dynamic effects, and the process of data evaluation were added to the static calibration results. In the end, the overall relative measurement uncertainty of 0.018 % at 4.5 min^{-1} is slightly higher than the target uncertainty of 0.01 %.

The rotational speed was measured for six shaft revolutions as for the torque calibration for a synchronous measurement of mechanical power. Based on the above-mentioned measurement uncertainty contributions, the traceability chain of the rotational speed measurement was established. The development of the transfer standard for rotational speed measurement is documented in deliverable D2: *'Report describing the requirements of tachometers such as the evaluation of existing tachometer measuring principles and their capabilities, and the procedure developed to calibrate tachometers with an uncertainty of 0.01 %'*

Traceable mechanical power determination

Using the synchronisation technologies of different data acquisition systems, an adequate protocol for the synchronisation of torque and rotational speed as a mechanical power transfer standard is implemented to perform the mechanical power determination. Based on the presented in-situ calibrations of torque and rotational speed measurement, test bench operators can benefit from knowing the deviation between their internal measuring instrument and a traced national standard and correcting for this deviation to obtain a more accurate mechanical power measurement result.

After the successful calibration in the 4 MW nacelle test bench at CWD and DyNaLab using the newly developed mechanical power transfer standard with an uncertainty lower than 1 %, the deviations were evaluated. Compared to the mechanical power measured by the mechanical transfer standards, the test bench at CWD measured ca. -5 % deviated mechanical power. For comparison, the test bench at FhG measured ca. +4 % deviated mechanical power. The results show the great importance of traceable mechanical calibration.

Using the previous calibration and this good practice guide, an additional measurement campaign at CWD with a different device under test (DUT) concept was successfully performed to measure the efficiency with an uncertainty less than 1 % without the help of the transfer standards.

To achieve traceable mechanical power in NTBs through methods for the interpretation of traceability sources and realization of measurement procedures, deliverable D4: '*Good Practice Guide on the calibration procedure for traceable mechanical power measurement based on synchronised torque and rotational speed measurement*' was published. It consists of the calibration procedure using transfer standards and the corresponding measurement uncertainty estimation, introduced as important background information for a comprehensive understanding of measurement traceability on NTBs. And an instruction describing the implementation of the acquired calibration results (certificates) for future measurement campaigns. By following this good practice guide for mechanical power determination, the mechanical input of DUTs can be determined more reliably within an uncertainty interval.

Summary

In alignment with Objective 2 – the development of a good practice guide for traceable measurement methods with a target uncertainty below 0.5 % for mechanical power – this project has significantly advanced the field. The objective aimed at achieving traceability in torque and rotational speed measurements up to 5 MN m, accompanied by synchronised measurements on both low and high-speed shafts.

The project successfully calibrated a 5 MN m torque transducer up to 1.1 MN m, establishing it as a torque transfer standard. Despite narrowly missing the targeted uncertainty of 0.5 %, practical solutions were devised, including a new extrapolation method. The operational readiness of PTB's 5 MN m torque standard machine, although delayed, remains crucial for future traceability.

A stator-less tachometer, calibrated and implemented as a transfer standard for rotational speed, was chosen to meet the project's requirements. While the overall relative measurement uncertainty slightly exceeded the target, it was crucial in establishing a traceability chain for rotational speed measurement.

The project implemented synchronisation technologies for torque and rotational speed, creating a mechanical power transfer standard. In-situ calibrations and successful applications in nacelle test benches demonstrated the importance of traceable mechanical calibration. The Good Practice Guide provides a comprehensive framework for achieving traceable mechanical power in nacelle test benches, enhancing reliability in mechanical input determinations.

The project successfully achieved Objective 2 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%.

4.3 Traceable electrical power measurement

Objective 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.

The measurement of electrical power is crucial to the measurement of the efficiency of nacelles. These measurements are needed for design optimisation and quality assurance. In these domains, the need for traceability is well established; all stakeholders desire traceable measurements. The theoretical concept is usually clear, but the practical application of the concept is challenging, leading to. compromised traceability. To ensure the proposed solutions in the good practice guide are practically viable and efficient, the guide's solutions were implemented and used in practice. Additionally, a system for estimating mechanical properties was validated.

These practical solutions consist of:

- Set-up and calibration of a reference power measurement system.
- In-line, on-site calibration of the test benches' electrical power measurement system (Figure 4) against the reference power measurement system.
- Torque and rotational speed estimation based on electrical quantities ("air gap torque").

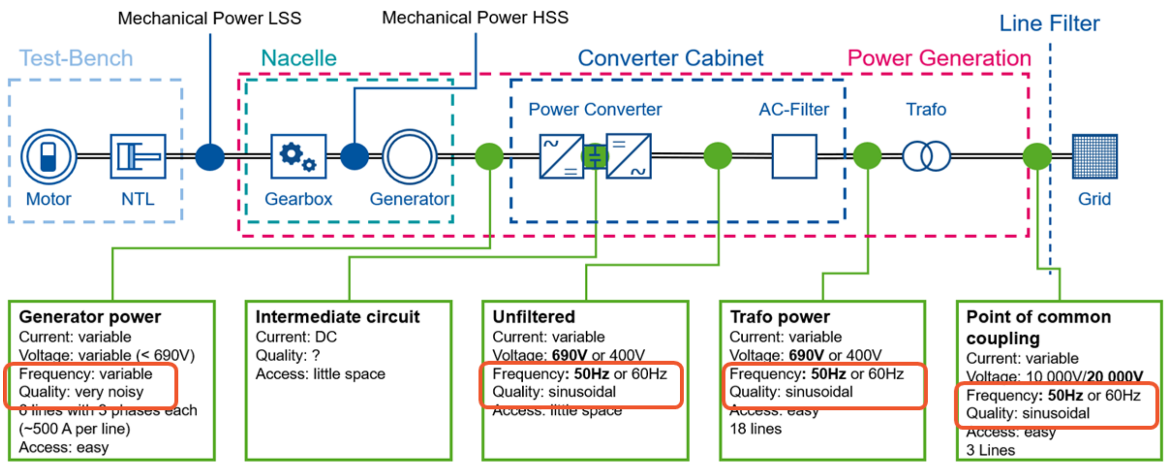

Figure 4: Typical test bench locations for electrical power measurement

Set-up and calibration of a reference power measurement system

Devices to be calibrated are usually sent to calibration laboratories, such as national metrology institutes (NMIs). However, the electrical power measurement systems of nacelle test benches (NTB) are integrated into the test bench and cannot be separated and sent for a meaningful calibration. Moreover, the on-site electro-magnetic environment is significantly more challenging than that of a calibration's lab. However, the most obvious alternative, the commercial transfer standards used as black-box devices, does not yield acceptable uncertainties. Therefore, within the project, the requirements for such calibration devices were identified by the NMIs (METAS, PTB and VTT) with the help of the test benches' operators RWTH and FhG, and a reference power measurement system was set-up. While composed of commercial equipment, the system can be split into individually calibrated parts and easily transported to the test benches. The calibration programme, namely including non-fundamental signal components, is adapted to match the conditions in the NTB. Since the system was calibrated against the NMI's primary standards, the uncertainty is that of a typical NMI's secondary working standard.

The reference power measurement system (Figure 5) includes 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. For calibrating the voltage transformers, a reference voltage divider was designed.

Moreover, to measure the current, current transformers were purchased and calibrated. The good practice guide contains recommendations for the requirements of these components.

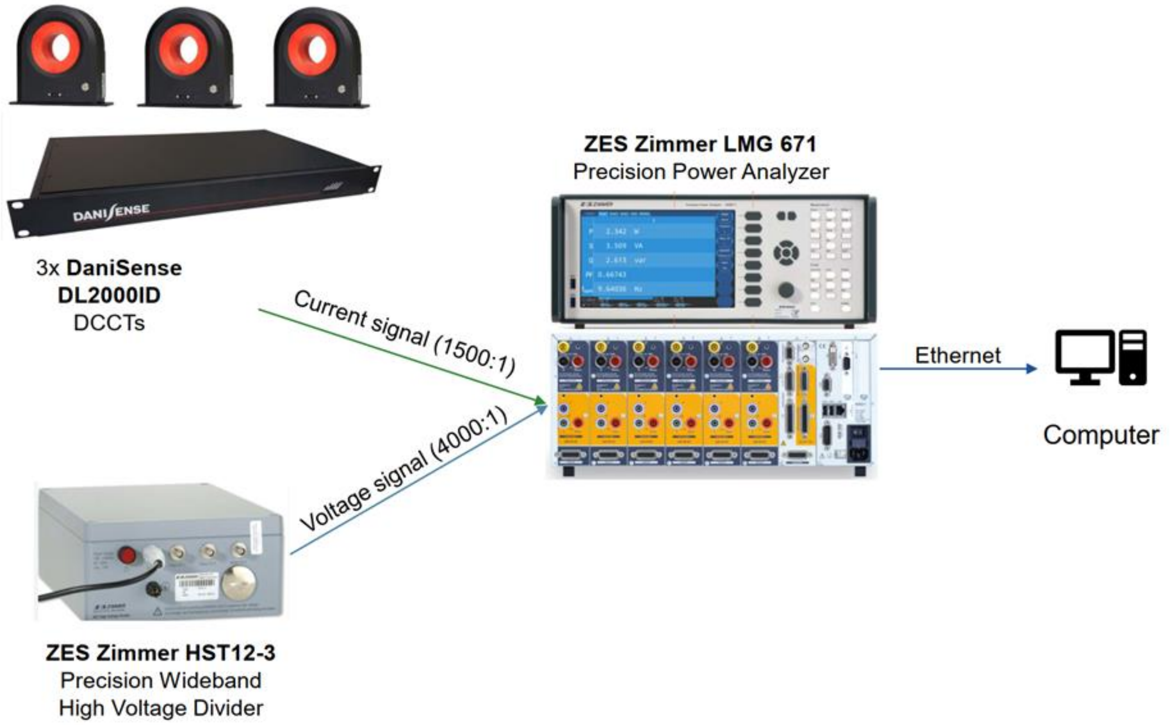

Figure 5: Typical configuration of a reference power measurement system.

In-line, on-site calibration of the test benches' electrical power measurement system

Since it is not convenient to send the nacelle test benches' (NTB) entire electrical power measurement system for calibration to an NMI, the NMI-grade reference power measurement system developed by METAS, PTB and VTT was sent to the NTBs at RWTH and FhG. The added value of this approach is manifold.

- The entire electrical power measurement system, including instrument transformers or sensors and cables, can be calibrated against an NMI-grade reference power measurement system.
- The calibration is carried out with minimum disruption to the NTB's operation. Namely, the NTB does not need to be taken apart for the electrical power measurement system to be sent to an NMI and reassembled after calibration and stay out-of-order during the whole, lengthy process.
- The calibration can be carried out during the normal operation of the NTB; the reference power measurement system on-site can be set-up while the NTB is adapted, for instance, to a new DUT (nacelle). This adaptation usually takes much longer than the set-up of the reference power measurement system.
- The calibration points correspond, by the nature of the approach, to the practical operating points used for nacelle testing. This includes also the electro-magnetic environment, which is particularly important given the length and layout of the cables in the NTB.
- During the calibration, the data acquisition is carried out as usual. Therefore, no unintentional differences – such as different software operating systems using different libraries, potentially changing the algorithms used – can affect the validity of the calibration.

The reference power measurement system was used for calibration (Figure 6) at DyNaLab at Fraunhofer IWES, Germany, and in the 4 MW nacelle system test bench at CWD at RWTH Aachen University, Germany. *In-situ* calibration of voltage dividers at DyNaLab was not possible, requiring external calibration using the reference voltage divider designed within the project. Besides linearity and frequency response measurements, the translation measurement deviations and the phase displacement were determined (Figure 7). Due to the influence of receivers and transmitters, burden and channel dependency of the receiver and the transmitter dependency were analysed additionally.

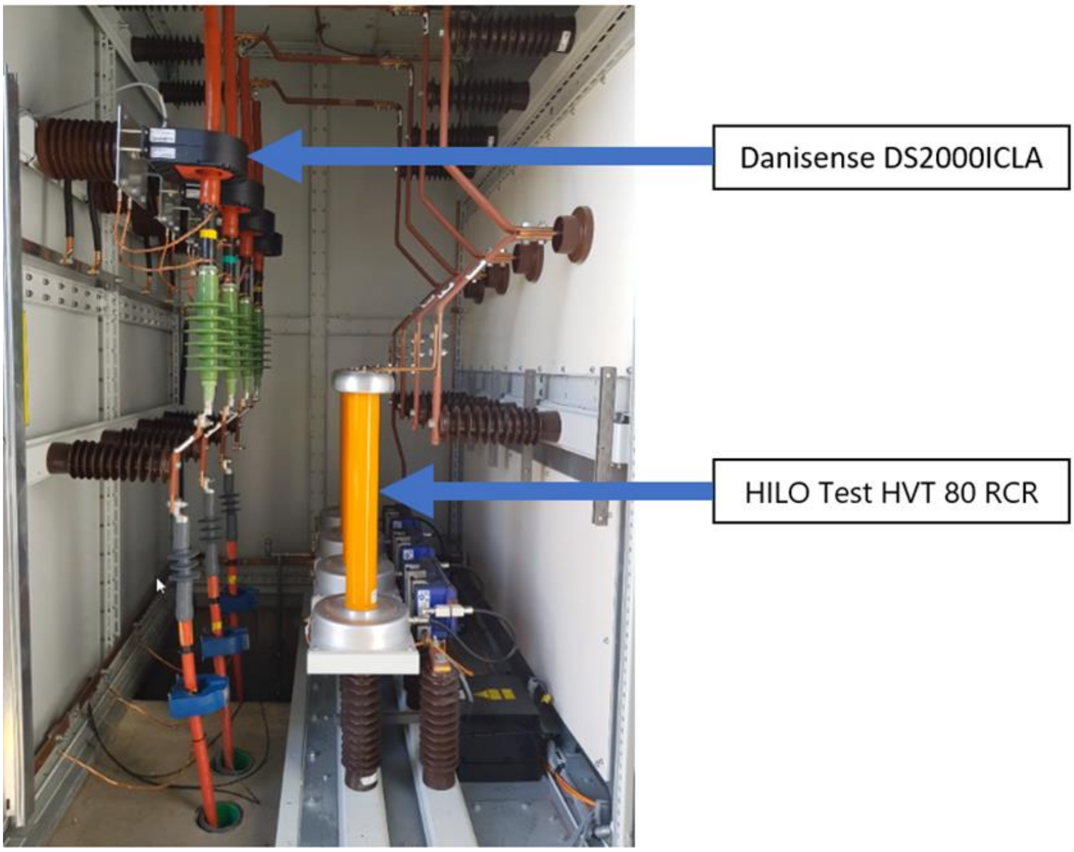

Figure 6: Current and voltage sensors of the reference power measurement system installed in an NTB.

Important observation:

Achieving electrical power measurement with meaningful uncertainties is easy, even in nacelle test benches. However, this requirement must be considered during NTB design, as some design choices can lead to systems with limited metrological stability that cannot be corrected by calibration. Retrofitting can be challenging, even if a better solution would have come at a moderate to even zero extra cost if implemented from the beginning.

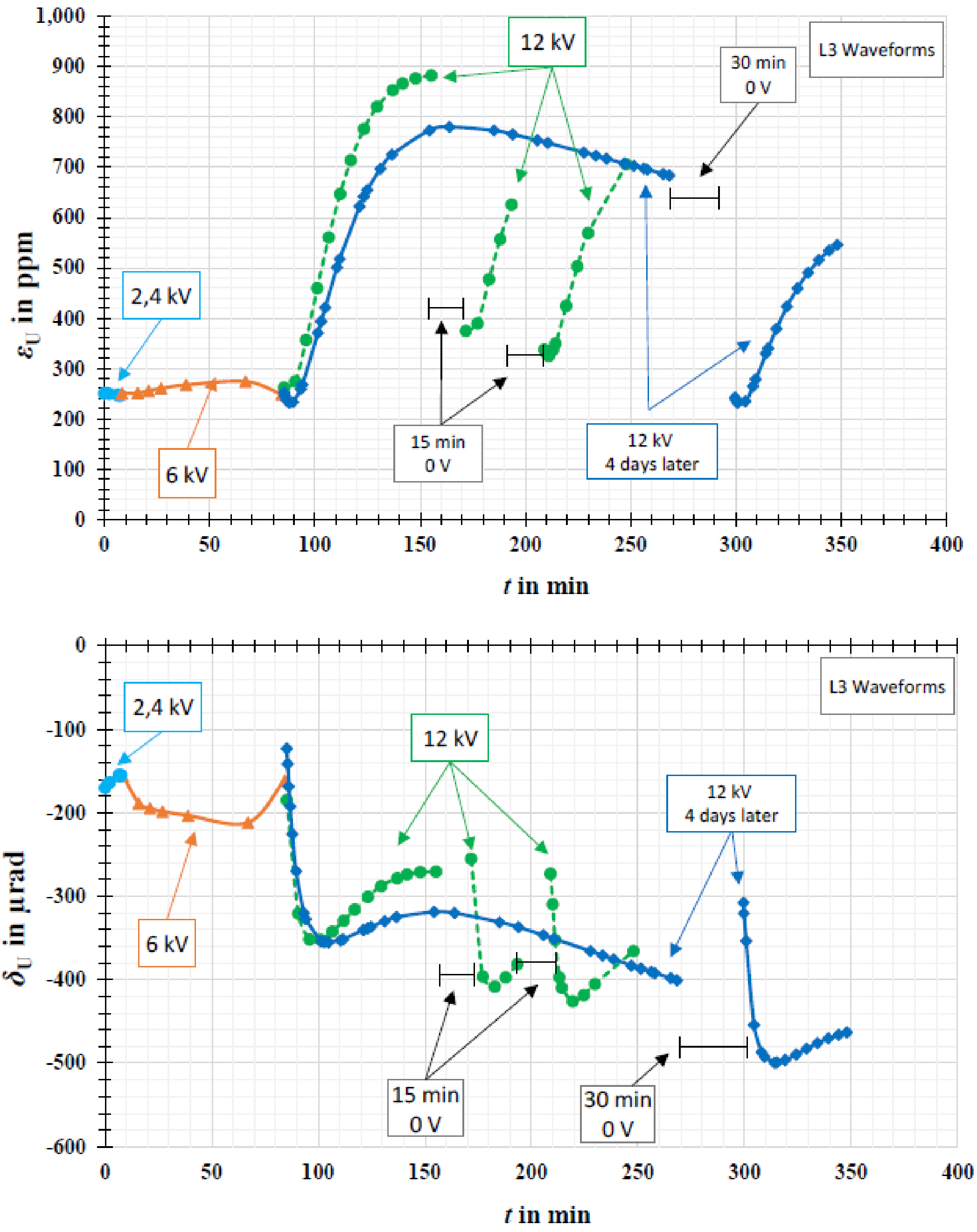

Figure 7: Measured dividing ratio error (top) and phase displacement (bottom) of a voltage divider, highlighting the drift.

Torque and rotational speed estimation based on electrical quantities ("air gap torque")

A software called "TorqueWind" was developed to calculate the air gap torque in the generator. The calculations are 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 air gap torque. To validate the software, the input torque was measured using a commercial torque transducer.

This approach allows the estimation of nacelle efficiency based on electrical measurements only. This is useful when a traceable mechanical power measurement is not available, either because the traceability is missing or because no suitable transducer is applicable on site.

Summary

In alignment with Objective 3 – the development of a good practice guide on traceable measurement methods for electrical power components – this project has successfully realised a comprehensive approach to implementing the theoretical principle of traceability in NTBs. The culmination of this effort is the development of a Good Practice Guide that seamlessly bridges the gap between theoretical foundations and practical solutions. This guide ensures an effective and efficient integration of traceability principles into NTB operations. Addressing three key practical questions of significant relevance, the guide outlines the establishment of a reference power measurement system for calibrating the electrical power measurement system of test benches, emphasizing the importance of calibration at a national metrology institute. Furthermore, it provides insights into the in-line, on-site calibration process for the electrical power measurement system of test benches, minimizing disruptions to their operational continuity. Lastly, the guide introduces a method for torque and rotational speed estimation, known as "air gap torque," relying solely on electrical quantities. This innovative approach enables efficiency estimation based on electrical measurements alone, eliminating the need for mechanical measurements. In essence, the good practice guide not only streamlines the application of traceability principles but also ensures the practicality and effectiveness of these measures in the dynamic environment of nacelle test benches.

Objective 3 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. The guide addresses key challenges, providing effective strategies for reference power measurement system setup, on-site calibration, and innovative torque estimation, ensuring the seamless integration of traceability principles into the dynamic operational environment of nacelle test benches.

4.4 Traceable efficiency determination of devices on test benches

Objective 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 will be developed.

Validation of the iso efficiency determination method

Iso-efficiency contours, also known as efficiency maps, have been used to characterize the efficiency of motors operated by variable speed drives across their entire operational spectrum. In this approach, the efficiency values for each operational point are determined using the direct method, which involves precise measurements of mechanical output power and electrical input power, along with monitoring the quality of the supply voltage. These measurements serve as the basis for calculating the iso-efficiency contours, as depicted in Figure 8.

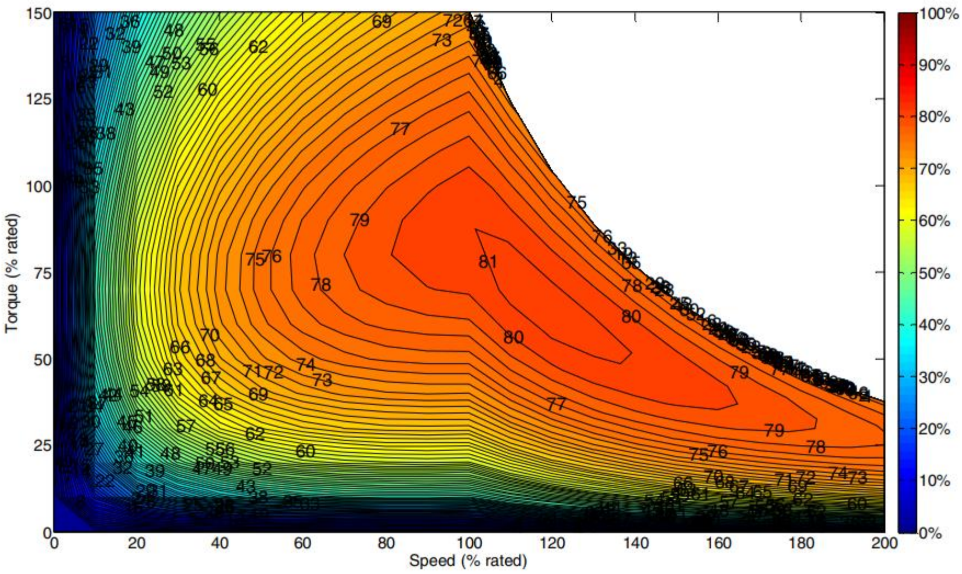

Figure 8: Analytical iso-efficiency contour example of an induction motor with 4 kW, 400 V, and a rated speed of 1500 min^{-1} taken from KS10[1].

This methodology has already found application in combustion engines and electric vehicle drivetrains. Determining the number of measurement points involves finding a balance between the accuracy of the iso-efficiency contours and the measurement effort. Like the direct efficiency determination according to IEC 60034-2-1, these measurements are conducted under steady-state conditions, meaning the motor operates at a constant speed and a constant torque load. To achieve this stable state, the motor operates at its rated values. Additionally, a temperature change of up to 5 K is allowed during the measurements.
It was observed in KS10 that there are more significant efficiency gradients in the lower speed and torque regions, requiring a greater number of measurement points in this range. Consequently, the distribution of measurement points across the motor's operational range may not be uniform.

In Figure 9 an example of operating points, the so called iso-efficiency map (Figure 9 a) and the sequence of load cycle combinations here referred to as the load sequence (Figure 9 b) is shown. For the load sequence, the rotational speed is periodically kept constant, with the torque gradually increasing and decreasing.

[1] KS10: **DOI:** 10.1109/ICELMACH.2010.5608035

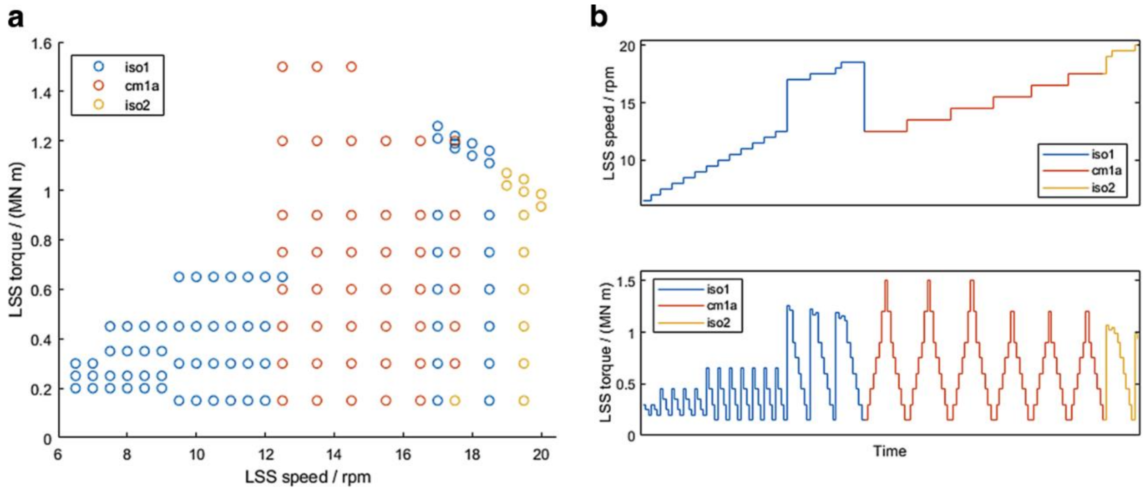

Figure 9: Iso-efficiency map (a) and load sequences (b) divided into three separate measurements, iso1, cm1a and iso2, which were performed on three different days.

Efficiency determination of a 2.75 MW nacelle on a 4 MW test bench

The efficiency of a 2.75 MW nacelle drivetrain on a test bench was determined traceably at various load points. For this purpose, so-called transfer standards for mechanical and electrical power measurement developed by PTB and METAS were additionally installed and integrated into the nacelle drivetrain. The measurement set-up is shown in Figure 10.

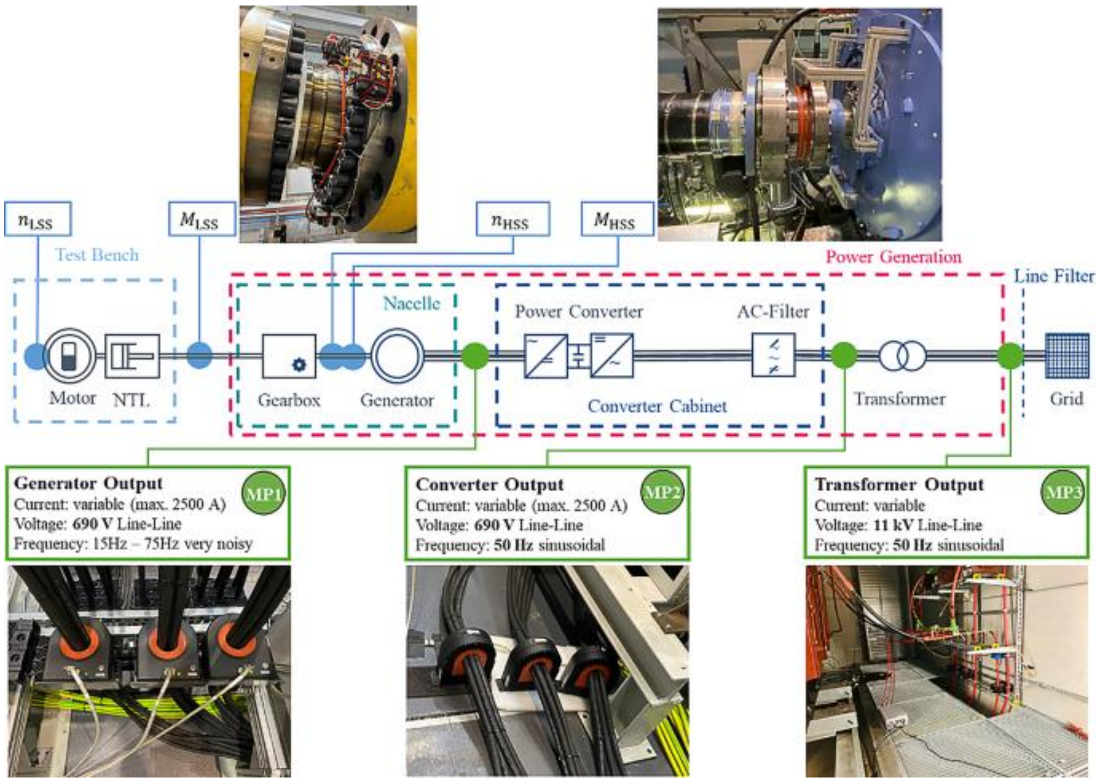

Figure 10: Measurement set-up at the Center for Wind Power Drives (CWD) of RWTH Aachen University in Aachen, Germany

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 electrical 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, 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 %.

Efficiency determination of a design study on a 10 MW test bench

Within the project a turbine has been 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 from PTB, as well as other mechanical and electrical sensors from NMIs 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 has been determined. Addressing the challenge in the measurement accuracy, state-of-the-art sensors, and measurement systems as well as calibration facilities have been used. The measurement points are shown in Figure 11.

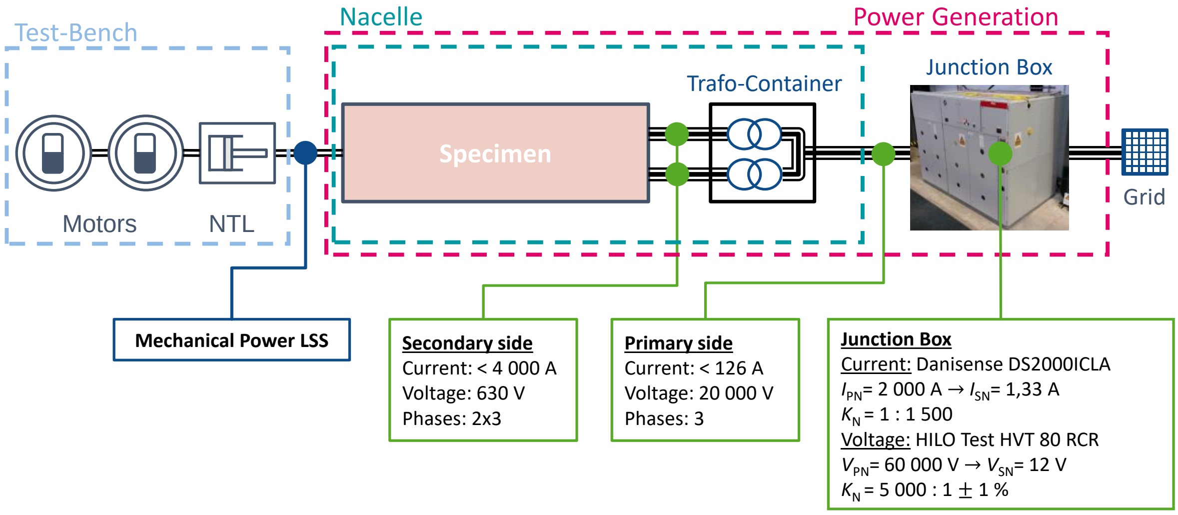

Figure 11: Equivalent circuit diagram of the test set-up and overview of the measuring points including required measuring devices at FhG IWES in Bremerhaven, Germany.

During the test campaign, numerous tests have been carried out serving various purposes. Because the measurement range of the Torque transducer is smaller than the rated torque of the turbine under test, all the tests were carried out in the under rated range of the turbine. Two tests were conducted and evaluated to demonstrate the method of efficiency determination. In both tests, the torque is held stable around the 5 MN m level to utilise the maximum capacity of the transducer. In the first test, the rotating speed follows an operational curve in a step manner upwards, while in the second test the rotating speed was kept constant to check the long-term behaviour of the turbine. For each test, the mechanical input power and the electrical output power were calculated for the determination of the efficiency.

The results show that an overall uncertainty level of 0.7 % is achievable for the efficiency determination with the torque measurement up to 5 MN m. As expected, torque measurement has contributed the largest part of the uncertainty. Surprisingly, the electrical power measurement has also contributed a large part to the uncertainty. This points out the fact that electrical power measurement needs equal care like the mechanical power, although it is generally considered as much 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 has been averaged, which results in almost negligible contributions in the overall uncertainty.

Error! Reference source not found.Error! Reference source not found.**Summary**

In alignment with Objective 4 – the development of a good practice guide for traceable efficiency determination on test benches with a target uncertainty of 1% – this project has successfully validated the efficiency determination procedure on diverse test benches. These include the 10 MW nacelle test bench and the generator test bench HiL-GridCoP at Fraunhofer IWES, Germany, as well as the 4 MW nacelle test bench at CWD, Germany. On the 10 MW NTB “DyNaLab” of FhG and the 4 MW CWD test bench, the efficiency of a 2.75 MW nacelle drivetrain was determined, achieving an overall system efficiency of 89% in the rated range with a relative expanded measurement uncertainty of up to 0.72%. Temperature dependency emerged as a significant factor in drive train efficiency, underscoring the need for a standardized procedure incorporating torque, rotational speed, and temperature. In a subsequent measurement campaign on the same test bench, the configuration of the DUT was altered, and using calibration results from the initial campaign, the efficiency of the new DUT concept was successfully determined with traceable uncertainty estimation. This resulted in an overall system efficiency of 93% in the rated range, with a relative expanded measurement uncertainty up to 0.94%, achieved without the need for installing transfer standards. Additionally, a turbine's efficiency was tested on Fraunhofer IWES' 10 MW nacelle test bench, utilizing precise measurements, including a 5 MN m torque transducer from PTB and other sensors. Results revealed a 0.7% uncertainty in efficiency determination, with torque measurements playing key roles.

Objective 4 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%.

5 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.

6 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
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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/

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