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Need for a traceable efficiency determination method of nacelles performed on test benches

A R T I C L E I N F O

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A B S T R A C T

For an energy transition towards renewable energy sources, the importance of traceable efficiency determination increases. There are standards for a traceable efficiency determination of rotating electrical machines as well as standards for a power curve determination of wind turbines in the field. To speed up and ameliorate the design process of a wind turbine, however, a standardised efficiency determination method for nacelle drive trains on test benches is required. In this paper, the need and recommendations for such an efficiency determination method are given.

1. Introduction

Wind turbines convert kinetic wind energy into electricity. The ratio between the electricity power output, P_{out}, of a wind turbine and the wind input in form of mechanical power via the rotor, P_{in}, is called energy conversion efficiency, η:

$$\eta = \frac{P_{out}}{P_{in}}. \quad (1)$$

In the design process of a wind turbine its performance must be predicted. The performance is a function of the rotor design and the mechanical-electrical efficiency of the nacelle's drive train. To ensure security, resilience and a high reliability of the power production, extensive testing of prototypes is of great importance. The nacelle of a wind turbine can be tested on special test benches (Fig. 1). Many tests and validation methods for product design and quality assurance are already standardised. The efficiency determination of nacelles and their components on test benches, however, is neither standardised nor traced to national standards hitherto.

In September 2020, the project "Traceable mechanical and electrical power measurement for efficiency determination of wind turbines" [1], short WindEFCY, started within the framework of the European Metrology Programme for Innovation and Research (EMPIR). The eleven international partners on this project work across disciplines to develop methods for traceable mechanical and electrical power measurement and for the efficiency determination of nacelles on test benches. This paper summarises the first output of the project describing different methods of evaluating the performance of wind turbines and ways of determining the efficiency of motors and generators. Based on these already available performance standards for wind turbines and the standards for direct and indirect efficiency determination of rotating electrical machines, the need and recommendations for an efficiency determination of nacelles in test benches is given.

2. Power analysis of wind turbines

So far, the efficiency of a wind turbine can be expressed in form of a power curve and the efficiency of a nacelle can be determined by calorimetric and back-to-back measurements. All methods have drawbacks. A power curve is performed in the field. It considers the rotor power; however, it is weather-depending, and reproducibility is only possible up to a certain amount depending on the surrounding topology. The calorimetric method, so far, lacks traceability of the torque measurement which makes up a large proportion of the uncertainty. The back-to-back method is not applicable on all test set-ups and the temperature influence still needs to be assessed. Moreover, all three methods are very time-consuming.

2.1. Power curve method

The performance of a wind turbine is expressed in a so-called power curve that maps the electrical power output to the wind speed at hub height. The standardised testing procedure to determine the power curve of a single grid-connected wind turbine is specified in IEC 61400-12-1 [3].

To perform the measurements, a test site with minor variations from a plane and without larger obstacles is required. One key element is measuring the correct wind speed at hub height not being influenced by the rotor flow field. The longitudinal and lateral, but not the turbulence, components of the undisturbed wind are measured by a cup anemometer, which must be calibrated before and after the measuring campaign. To determine the net electrical power output of the wind turbine, current and voltage on each phase are to be measured. To this end, a power analyser shall be placed between the wind turbine and the electrical connection.

Prior to calculating the power curve, the data is to be normalised: (1) to the air density at sea level (1.225 kg/m^3) and (2) to the air density averaged over the periods of valid data collection. After that, the data needs to be sorted according to the method of bins. The data base should embrace wind speeds from 1 m/s below cut-in speed up to the wind

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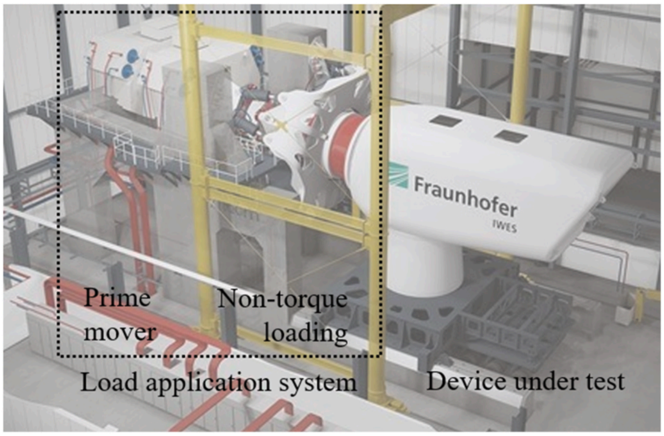

Fig. 1. CAD-model of the nacelle test bench *DyNaLab* at Fraunhofer IWES showing the load application system (LAS), consisting of a prime mover and a non-torque loading (NTL), and the device under test (DUT). Modified based on [2].

speed at 85% rated power times 1.5. The bins should cover a wind speed range of 0.5 m/s over 10 minutes. For each bin i, both the mean of the normalised wind speed, V_i, and the normalised power output, P_i, is calculated:

$$V_i = \frac{1}{N_i} \sum_{j=1}^{N_i} V_{n,i,j}, \tag{2}$$

$$P_i = \frac{1}{N_i} \sum_{j=1}^{N_i} P_{n,i,j}, \tag{3}$$

where $V_{n,i,j}$ is the normalised wind speed at data set j in bin i, $P_{n,i,j}$ is the normalised power output of data set j in bin i, and N_i is the number of 10 min data sets in bin i. Based on that, a normalised and averaged power curve can be given, which, again, can be used to forecast the annual energy production.

The combined standard uncertainty $u_{c,i}$ of the power in bin i is given by

$$u_{c,i}^2 = \sum_{k=1}^{M} \sum_{l=1}^{M} c_{k,i} u_{k,i} c_{l,i} u_{l,i} \rho_{k,l,i,j}, \tag{4}$$

where $c_{k,i}$ is the sensitivity factor and $u_{k,i}$ is the standard uncertainty of component k in bin i, M is the number of uncertainty components in each bin, and $\rho_{k,l,i,j}$ is the correlation coefficient between uncertainty component k in bin i and uncertainty component l in bin j.

2.2. Calorimetric method

In nacelle test benches, an existing method to determine the efficiency of devices under test (DUTs) is the calorimetric method that quantifies the power losses, P_{loss}, in form of heat:

$$\eta = \frac{P_{out}}{P_{in}} = \frac{P_{in} - P_{loss}}{P_{in}} = 1 - \frac{P_{loss}}{P_{in}}. \tag{5}$$

This method is used due to the advantageous measurement accuracy of power loss measurements. The heat originates from mechanical friction, lubrication, and losses in the electrical systems and is normally emitted into the surroundings via conduction, convection, and radiation. To measure this heat, a new boundary including additional measurement equipment needs to be created. In Ref. [4] this boundary was created in form of an isolation housing that was wrapped around the DUT.

The DUT for the efficiency quantification in Ref. [4] was an integrated drive train. It consisted of a planetary gearbox and a permanent-magnet mid-speed synchronous generator. The temperature in the drive train was regulated by an oil and water-cooling system. The insulation housing minimises the thermal output into the environment, consequently, most of the heat was emitted through the active cooling system. Once a thermal equilibrium inside the insulation housing is reached, the heat loss is of the same amount as the heat conducted by the cooling system. This main heat loss, $P_{conv,\ water}$, can be calculated by the volumetric flow rate and the temperature difference between outlet and inlet. More details and further shares of the power loss are listed in Ref. [4].

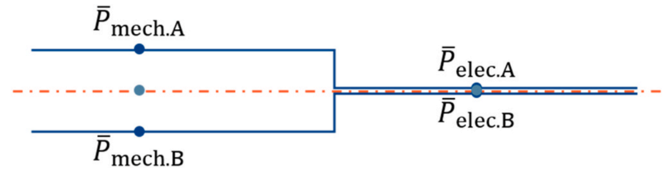

Fig. 2. Mean values of mechanical and electrical power in the two test modes (A) and (B). Taken from Ref. [6].

The input power, P_{in}, is made up of the mechanical and the electrical input power:

$$P_{in} = P_{in,mech} + P_{in,elec}. \tag{6}$$

The mechanical input power, $P_{in,mech}$, is calculated from the input torque and the rotational speed, which are both not yet traced to national standards. While the electrical input power, $P_{in,elec}$, is calculated from the data sheet of the electrical oil pumps.

A warm-up period optimised measurement approach is going from small to large input powers and waiting at each step until a thermal equilibrium is reached. The operating points are defined by input torque and input rotational speed. The measurands are averaged over several minutes.

With errors below 0.5%, this method is suitable for validating even small improvements of efficiency close to 100% efficiency. However, it cannot be used to determine the efficiency of entire multi-megawatt nacelles due to their size and the time consumption to reach a stationary temperature state at the current operating point.

2.3. Alternative back-to-back method

A method to determine the efficiency of nacelles on test benches directly is described in Refs. [5,6]. For that method, the test bench and the nacelle under test are connected back-to-back and operated in two modes with opposite energy flow directions: (A) normal mode where the prime mover acts as the motor and the nacelle as the generator, and (B) reverse mode where the nacelle is the motor and the prime mover is the generator. For this method, only one nacelle is required.

In both modes the same machines, the same measuring chains, the same rotational speed in opposite directions, and similar load cases and conditions evoked by the active controlling are used. Depending on the measurement scenario, either the torque load or the electrical power is taken as a reference for the two operating modes (Fig. 2). The torque is measured on the connecting shaft between the motor and the generator, while the electrical power is measured between the generator and the power converter. The temperature of the bearing and the generator must be similar in both modes.

To calculate the efficiency in normal mode (A), the mean values of mechanical, $P_{mech.A}$, and electrical power, $P_{elec.A}$, are used:

$$\eta = \frac{\bar{P}_{elec.A}}{\bar{P}_{mech.A}} = \frac{\bar{P}_{elec.A}}{\bar{P}_{elec.A} + \bar{P}_{Loss.A}} = \frac{\bar{P}_{elec.A}}{\bar{P}_{elec.A} + k_A \bar{P}_{Loss.total}}, \tag{7}$$

where the proportion factor k_A is the amount of power losses in mode (A) on the total power losses, $P_{Loss.total}$. The mechanical power is averaged in

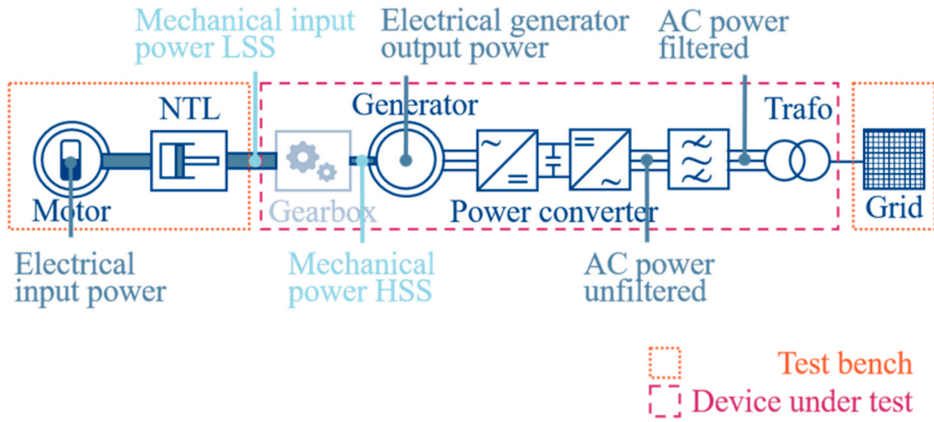

Fig. 3. Schematic diagram of the set-up of a test bench including a nacelle as a DUT. Based on [14]. Possible measuring points for mechanical and electrical power measurement are shown.

the angle domain and sets the averaging period for the electrical power that is averaged in the time domain.

To calculate the total power losses, the sum of the differences in the mechanical and electrical power in both modes (A) and (B) is formed:

$$\overline{P}_{\text{Loss.total}} = \overline{P}_{\text{mech.A}} - \overline{P}_{\text{mech.B}} - \overline{P}_{\text{elec.A}} + \overline{P}_{\text{elec.B}}. \tag{8}$$

The uncertainty of the total power losses is, hence, only depending on the uncertainties of the mechanical and electrical power changes. At rated power an expanded uncertainty ($k = 2$) of less than 1% for the determined efficiency can be achieved. In the presented test set-up, five measurements per operating mode distributed over the entire electrical power range were performed.

The main disadvantage of the back-to-back method is the time-consuming measurement effort as all operating points have to be met twice. Since some types of losses, e.g., stator winding losses, are temperature-dependent, the temperature of the test object should be as equal as possible in both directions of power flow. Moreover, not all test set-ups can be run in reverse mode.

3. Efficiency determination of rotating electrical machines

The standard for determining the losses and the efficiency of rotating electrical machines from tests is IEC 60034-2-1 [7]. According to Ref. [7], the tests performed can be grouped into three categories: direct, back-to-back, and indirect power measurement as a base for an efficiency determination.

Using the direct method, the input-output power measurement is performed on a single machine. In the back-to-back method the electrical input and output power on two identical machines being mechanically connected back-to-back is measured. In doing so, measuring the mechanical power, which is tainted with a relatively large measurement uncertainty [8], can be avoided. For the indirect method, the actual loss comprised of certain losses in a machine is determined. The test method highly depends on the type of machine tested. The direct efficiency measurement method is only recommended for induction machines with a rated power <1 kW because of the relatively large measurement uncertainty of the mechanical power measurement [8]. Above a rated power of 1 kW, the indirect efficiency determination method or the single loss procedure is to be applied. The dissipated mechanical power, P_{out}, is calculated as the difference of the sum of the separately determined losses from the consumed electrical power, P_{in}:

$$P_{\text{out}} = P_{\text{in}} - P_{\text{Cu1}} - P_{\text{Fe}} - P_{\text{Rb}} - P_{\text{Cu2}} - P_{\text{LL}}, \tag{9}$$

where P_{Cu1} are coil copper, P_{Fe} iron (magnetisation and eddy current losses), P_{Rb} friction, P_{Cu2} rotor copper, and P_{LL} are residual losses. The load-dependent residual losses can either be computed via a mathematical function or by determining the residual losses for different load points in the range from 25% to 125% of the rated machine torque.

4. Efficiency determination in nacelle test benches

In the following, recommendations for an efficiency determination procedure based on the information from the previous chapters are made. The choice of test to be performed in order to determine the efficiency of any nacelle depends on the size and type of the nacelle and its components, the available test equipment, and the accuracy required.

Size and type of nacelles and their components being tested vary a lot. The world's most powerful onshore wind turbines have a rated power of 7.58 MW [9], while the most powerful offshore wind turbines can produce up to 14 MW [10,11]. The two types of wind turbines on the market are: direct-drive wind turbines where the synchronous generator is directly powered by the rotor, and medium- or fast-speed wind turbines with gearboxes increasing the rotor speed of typically up to 25 min^{-1} on the low-speed shaft (LSS) to up to 1600 min^{-1} on the high-speed shaft (HSS). These high-speed values are more appropriate for driving a doubly fed induction generator. Most wind turbines are stall- or pitch-regulated and operate on variable wind speeds with a certain cut-in and cut-out speed as the operating limits of the wind turbine.

As wind turbines differ a lot, the available test equipment is manifold too. For a simple end of line test (EoL), a common practice is to operate two nacelles back-to-back where the driving nacelle is in speed-controlled mode. For a more detailed testing, i.e., of prototypes, nacelle system test benches can perform Hardware-in-the-Loop (HiL) tests. In doing so, the rotor power coefficient can be simulated. For those tests, the nacelle's controller is activated, and it controls the variables electrical output power and generator speed. Therefore, the test bench controls the input torque.

Within the project WindEFCY, the target uncertainty for the efficiency determination on test benches is 1%.

1. A reliable efficiency determination is based on traceable mechanical and electrical power measurement and an adequate synchronisation of both amongst each other. Within the project WindEFCY, both the mechanical and the electrical power measurement in test benches are planned to be calibrated via transfer standards.
2. The transfer standard for mechanical power measurement consists of torque and rotational speed measurement. It must be installed directly at the rotor hub of the nacelle, which is the input to the nacelle, on the LSS (Fig. 3).
3. The transfer standard for electrical power measurement consists of a power analyser as well as current and voltage sensors (Fig. 3).

4. All signals are to be sampled and filtered with an adequate frequency. The measured values are to be averaged over an integer multiple of shaft revolutions [12]; the same for all different rotational speeds.
5. In order to investigate the influence of temperature and humidity, both are to be recorded permanently at all reference points for mechanical and electrical power measurement.
6. Zero signals are to be taken before the load cycle. This is especially relevant for the mechanical power measurement as the offset in the torque measurement is to be corrected for.
7. The segregation of loss method with linked temperature corrections as required for an indirect efficiency determination is not applicable in test benches due to the complexity of nacelles and the lack of idle running possibilities in some nacelles. Consequently, a high accuracy of the mechanical power measurement is needed to determine the efficiency using the direct method.
8. To determine the efficiency of drive systems at different load points, so-called efficiency maps or iso efficiency contours as explained in Ref. [13] can be used.

5. Conclusion and outlook

This paper gives an overview of different methods to determine the efficiency of nacelles on test benches and of standardised direct and indirect efficiency determination procedures for rotating electrical machines. It was found that the currently available standards and methods have several drawbacks and mostly do not meet the project's target uncertainty of 1%.

Within the EMPIR project WindEFCY a newly developed efficiency determination method based on calibrated and synchronised mechanical and electrical power measurement will be tested on two different test benches: (1) at the *DyNaLab* of Fraunhofer IWES and (2) at the *Center for Wind Power Drives (CWD)* of RWTH Aachen University. Additional investigations and research include the influence of rotational speed on torque measurement and the acquisition of the electrical measurands, especially in the case of signals that are heavily affected by harmonics due to the use of frequency converters. Signal processing and filtering are of great importance here, especially regarding synchronisation with the acquisition of the mechanical measurands.

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