Deliverable D1 within 19ENG08

- Summary report 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 -

Authors: Maximilian Zweiffel (RWTH)
Juan Manuel Quintanilla Crespo (CENER)
Lukáš Vavrečka (CMI)
María A. Sáenz-Nuño (Comillas Pontifical University)
Javier Maldonado (DINNTECO)
Norbert Eich (FhG)
Hongkun Zhang (FhG)
Janusz Fidelus (GUM)

Rafael S. Oliveira (Inmetro)
Christian Mester (METAS)
Christian Lehrmann (PTB)
Zihang Song (PTB)
Nijan Yogal (PTB)
Johannes Teigelkötter (THAB)
Eusebio Bernabeu (Universidad Complutense de Madrid)
Timo Kananen (VTT)
Paula Weidinger (PTB)

DOI: 10.5281/zenodo.4733780

This report has been produced within the EMPIR project entitled *Traceable Mechanical and Electrical Power Measurement for Efficiency Determination of Wind Turbines* or *19ENG08 WindEFCY.* More information about this collaborative research project can be found on the project's website https://www.ptb.de/empir2020/windefcy/home/. This report aims to investigate the multitude of influencing variables and the changing boundary conditions for measurements to determine the efficiency of wind turbines. Moreover, through a systematic comparison of direct and indirect efficiency determination methods for rotating electrical machines, the challenges for designing an efficiency determination procedure for nacelles and their components on test benches is examined.

Disclaimer

Any mention of commercial products within this report is for information only; it does not imply recommendation or endorsement by the partners in this project.

The views expressed in this report are those of the authors and of the EMPIR 19ENG08 WindEFCY project team.

Acknowledgement of funding

The production of this project and, therefore, this report was funded by the European Metrology Programme for Innovation and Research (EMPIR). The EMPIR initiative is co-funded by the European Union's Horizon 2020 research and innovation programme and the EMPIR Participating States.

Authorship

The preparation of this guide was led by Maximilian Zweiffel of the Rheinisch-Westfälische Technische Hochschule (RWTH), Aachen (Germany) with extensive input from all members of the EMPIR 19ENG08 project team. The discussion and input of all the partners in the project and their colleagues are greatly appreciated.

Suggestion for the quotation of the references

M Zweiffel *et al*, 2021. Deliverable D1 within 19ENG08: Summary report 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. DOI: 10.5281/zenodo.4733780

Project logo

DOI: 10.5281/zenodo.4733780

Content

DOI: 10.5281/zenodo.4733780

1 Introduction

This report was generated in work package 1 (WP1) of the EMPIR project 19ENG08 "Traceable mechanical and electrical power measurement for efficiency determination of wind turbines" short WindEFCY. The aim of this report is to investigate the available power and efficiency determination methods of wind turbines and nacelles, as well as the necessary synchronisation and data transmission technologies. The outcome will build a theoretical base for the further work packages of the project.

The energy transition towards renewable energy sources is accelerating and wind power takes the major share in this development. To further expose the potentials of wind power, wind turbines need to be highly innovative to reduce costs and improve performance. Cost reduction can be reached by using nacelle test benches (NTBs). Those can additionally increase performances of wind turbine as tests and validation can be performed at an earlier stage in the development process and before the turbine is installed in the field. In this context, standardised tests and validation processes for NTBs are needed to assure quality and reach comparability between different NTBs. As there are no standardised tests for the efficiency measurement on NTBs, this need is met within this project. A standardised efficiency determination method based on traceable measurements will enable a comparability of measurement data gathered on different test benches with uncertainties of less than 1 %.

Prior to developing a new and standardised efficiency determination procedure including load cycles, boundary conditions, and a measurement uncertainty (MU), knowledge about the state of the art and currently used power curve determination methods for wind turbines is gathered. Based on already existing efficiency determination methods for devices on NTBs, their potentials and challenges are elaborated and evaluated. Finally, the efficiency determination of rotating electrical machines in general is elaborated as this field is very well studied and standardised. Depending on the rated power and the demanded accuracy of the efficiency measurement, different direct and indirect measuring procedures can be applied. Experience from these standards and calibration procedures are evaluated and used to identify the most significant influencing factors on the measurement result. To this end, the different existing methods for wind turbines are compared to each other regarding their accuracy, applicability, and traceability. Moreover, efficiency determination methods which are currently used in practice on NTBs are evaluated and compared with power curve determination methods in the field. Through a systematic comparison of direct and indirect methods for the determination of rotating electrical machines, where the ratio of output to input and the power dissipation are calculated respectively, their advantages and disadvantages are demonstrated. In this way, the challenges for designing an efficiency determination method for nacelles on NTBs is examined.

2 Existing efficiency measurement methods for wind turbines

The efficiency measurement of wind turbine drivetrains was no prioritised task in the past. Therefore, the existing guidelines rely on power curve measurements in the field. They show certain drawbacks by not considering the efficiency of the drivetrain in particular. However, those methods are carried out and compared to draw conclusions towards the methods to be created on the test bench.

2.1 Definition of power curve and power coefficient

As wind turbines covert kinetic wind energy into electricity, the conversion efficiency η can be described as the ratio between the wind power input P_{wind} and the electric power output P_{el}.

$$\eta = \frac{P_{\mathrm{el}}}{P_{\mathrm{wind}}}. \tag{1}$$

The wind power is calculated by the following equation using the mass of air $\mathrm{d}m/\mathrm{d}t$ flowing through the rotor sweep and the speed of air v. As the wind speed v is a more convenient variable, the mass flow dm/dt is often expressed as the product of wind speed v, air density ρ, and rotor sweep A.

$$P_{\mathrm{wind}} = \frac{1}{2} \cdot \frac{dm}{dt} \cdot v^2 = \frac{1}{2} \cdot \rho \cdot A \cdot v^3 \tag{2}$$

The aerodynamic power of the undisturbed wind field which flows through the rotor sweep is used as a reference for the rotor efficiency of a wind turbine. The rotor efficiency is then be regarded as the ratio of the mechanical power which is produced and the aerodynamic power. Regarding this, the conversion factor will be maximised if the wind speed after the rotor becomes zero, which is not possible from a physical point of view. Therefore, the mass flow has to be considered with the impulse theory of BETZ [1]. It describes the relation between the windspeed before v_1 and after v_2 the rotor. With this relation the conversion factor can be expressed by the following equation. [1]

$$c_{\mathrm{p}} = \frac{1}{2}\left[1 - \left(\frac{v_2}{v_1}\right)^2\right] \cdot \left[1 + \frac{v_2}{v_1}\right] \tag{3}$$

Using this formula, the power coefficient c_{p} can be calculated for every ratio of $v_1$and v_2. The results are shown in the following figure.

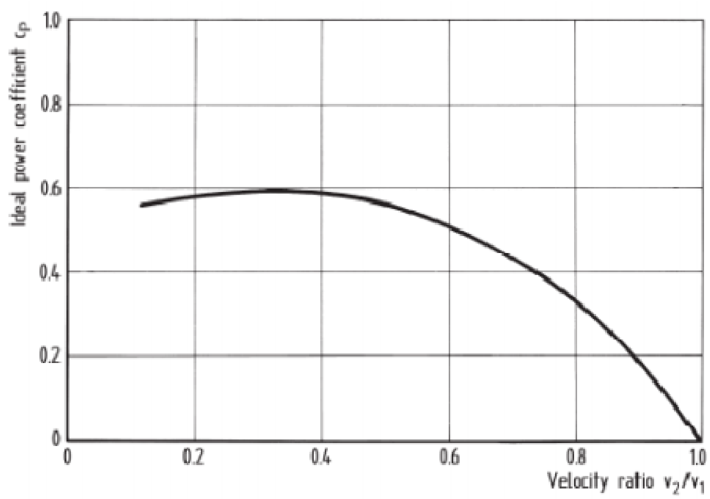


Figure 1: Ideal power coefficient and wind speed ratio before and after the rotor, [1].

It can be seen that the power coefficient reaches its maximum at $v_1/v_2 = 1/3$. The power coefficient at this ratio of input and output speed is $c_{\mathrm{p,max}} = 0.593$ and is called Betz-coefficient. Additionally to the power coefficient, a power curve can be calculated. It expresses the mechanical power output at certain

DOI: 10.5281/zenodo.4733780

wind speeds. With the power curve the estimated generated power can be calculated for different sites where the wind speeds are known [1].

The physical consideration gives a theoretical understanding of the power coefficient of a wind turbine. But the power coefficient is depending on many more influences than the input and output speed of the wind $v_1$and v_2. At first wind fields are irregular and show gradients. Furthermore, there are turbulences in real wind fields which are not regarded as well. Therefore, standardised measurements of the power coefficient in the field are necessary to compare different wind turbines and estimate their energy yield.

2.2 Measurement of the power curve and the power coefficient

To measure the power curves and power coefficients, there are certain guidelines describing methods. The most important of those is the IEC 61400-12-1:2017 [2]. Furthermore, there are other guidelines which also refer to IEC 61400-12-1 but are important for the certification of wind turbines as the MEASNET Guideline and the FGW Guideline.

2.2.1 IEC 61400-12-1

The IEC 61400-12-1 describes the measurement of the power curve and its method is generally accepted as a binding basis. Therefore it is used for the wind turbines official certificate of performance that is mandatory and must be guaranteed by the manufacturer.

The measurement of the power curve according IEC 61400-12-1 is performed in the field at a single wind turbine under standardised measuring conditions. It compromises detailed descriptions of the procedures, the test equipment and in particular the unavoidable uncertainties in the results. This includes the specification of the test site, the measurement of wind speed, the density and the measurement of the electric energy output. Additionally, the data acquisition (DAQ) and the data processing are specified.

As the measuring takes place in the field, the results are to a certain degree site specific. Also, not all parameters influencing the power curve are regarded, as for example the turbulence of the wind field. Furthermore, the measuring of the variables and the data processing has to be evaluated statistically as the wind speed cannot be influenced which comes along with uncertainties. Finally, the method is time consuming until a sufficient database is reached.

2.2.1.1 **Test site and wind measurement**

The choice of the test side allows just minor variations from a plane free from larger obstacles. To measure the correct wind speed on the test site, a meteorological mast is used. The position on the test site is important as an undisturbed wind speed is wanted. Therefore, the rotor sweep may not interact with the meteorological mast. Furthermore, interactions with other wind turbines have to be averted as well.

The measurement of the wind speed itself is performed on a single spot on the height of the rotor hub. It is performed using cup anemometers which only allow to determine wind speed in longitudinal and lateral direction, but neglect the vertical, turbulent flows. The cup anemometer needs to be calibrated before and after the measurement campaign.

2.2.1.2 **Electrical power measurement**

The electrical net power output of the wind turbine is measured using a power measurement device that measures current and voltage on all three phases. Current, voltage and power transducers should all fulfil the requirements of accuracy class 0.5. Furthermore, every peak of the measurement variables has to be measured. To achieve this, a measuring range of -25 % to 125 % of the nacelle's rated power is recommended. Additionally, it needs to be monitored if this requirement is fulfilled.

2.2.1.3 **Data acquisition**

The DAQ has to be proceeded until the data base is sufficient in order to statistically determine the power curve. The data shall be measured with a sampling rate of 1 Hz and cover at least a wind speed range extending from 1 m/s below cut-in speed of the turbine to 1.5 times the wind speed at 85 % of the rated power. After normalisation of the wind date regarding air density, the data is sorted using the method of bin procedure. The wind speed range of the bin should contain data of 0.5 m/s. Within the bins the means of normalised wind speed and normalised power output are calculated. The power values are 10-min mean values in each bin of velocity. The gathered data results in a reference wind speed frequency distribution. A Rayleigh distribution that is identical to the Weibull distribution with a shape factor 2 shall be used to calculate a normalised and averaged power curve. This power curve is then be used to calculate the annual energy yield based on standardised wind input data. Additionally, the power coefficient can be derived.

2.2.2 MEASNET Guideline

MEASNET, as the organization itself explains in their procedures and documents, is a network of measurement institutes which have been established to harmonise wind energy related measurement procedures. The institutes of MEASNET are all actively performing wind energy related measurements. Each institute has to document the skills and quality of measurements, to apply agreed “MEASNET measurement procedures” and to participate as required in mutual evaluation exercises.

2.2.2.1 *MEASNET Power performance procedure*

The Power performance procedure is the measurement procedure agreed upon by the MEASNET members to be mutually used and accepted. Generally, the IEC standard defines measurement and data analysis procedures thoroughly. Nevertheless, in any standard and also in the reference power performance measurement procedure, several parameters and alternatives can be chosen. MEASNET has decided to add additional requirements to the reference procedure, determining some parameters and alternatives as fixed in order to strengthen the quality and inter-comparability of the measurements. Deviations from these additional requirements shall be treated in the same way as in the IEC document.

This procedure, available at the MEASNET Web site is currently in version 5, dated December 2009 [3]. Within the procedure, MEASNET appoints that the procedure is based on the standard “Wind turbines – Part 12-1: Power performance measurements of electricity producing wind turbines. First edition 2005-12, IEC 61400-12-1:2005 (E) [4]. This document is used as a reference document.

However, the IEC 61400-12-1 standard is now at Edition 2, issued in 2017 [2]. Thus, the changes introduced in that revision have not been reviewed and included in the version of the MEASNET document.

2.2.2.2 *MEASNET measurement procedure additional requirements*

Going through the document, the following additional requirements for a power performance measurement of a wind turbine are found. They are reviewed in this chapter, indicating the relevance for the determination of the wind turbine efficiency.

Reference normative: IEC 60044-2:2003: Instrument transformers Part 2: Inductive voltage transformers [5]. All IEC standards refer to standards that define in more detail the equipment, such as voltage transformers used in the measurement and that may have influence in the measurement of power output given by the turbine and thus in the efficiency. Equipment built according to this standard should be installed for voltage measurements when applies and their class and uncertainty considered. However, this standard has been withdrawn and substituted by IEC 61869-3:2011 [6]. And so, this should be the standard to be taken into consideration at this point.

Calibration of cup anemometers must be performed by a MEASNET accredited institution before use in the measurement campaign and shall be re-calibrated after the campaign. In case of blade tip anemometers, a campaign end calibration is obligatory. MEASNET calibration differs slightly from other standards. This requirement might be relevant for a field measurement and field efficiency evaluation but loses somehow its importance when considering power performance in test benches as the rotation of the shaft can be implemented.

 DOI: 10.5281/zenodo.4733780

Additional requirements regarding wind measurements and anemometers such as re-calibration, condition monitoring through in-situ comparison, type of anemometer used and similar, are included in the MEASNET procedure. They have their influence on the power performance measurement mainly in terms of uncertainty calculation of the final results and possible deviations of the procedure.

Related to the **rotational speed and the pitch angle**, the document indicates that they shall be measured on a wind turbine with active power control. In addition to the electric power, these essential values serve for characterising the wind turbine behaviour. Wind turbine controller output signals may be used for this purpose. They can be used to assess more precisely the efficiency of the wind turbine when performed in a field test. Rotational speed, measured from control or possibly directly from the component, can also be used for efficiency calculations in laboratory tests.

Data collection: The criteria for the measurement of meteorological variables such as air pressure, air temperature, and humidity measurements, shall be carried out using appropriately calibrated sensors, together with rotational speed and blade pitch angle. They shall be carried out as 10-minute average values at a sampling rate of 1 Hz or higher. This is considered representative enough for capturing the behaviour of the wind turbine.

2.2.3 FGW Standard

As an amendment to the IEC 61400-12-1 Ed. 2 standard, the FGW – TG2 introduces additional specifications since 1998. As it is labelled, the standard does not refer to NTBs but to power curve determinations in the field in a way of measuring the wind as the input source and the electrical power as the output. The aim is to minimise the MU and to increase the reproducibility of the measurement results.

As a requirement, the accreditation of the measuring institute according to DIN EN ISO/IEC 17025 is defined. If those are met, FGW offers a conformity seal to emphasise the quality of work. Test reports created in this way serve as the basis for purchase agreements and finance commitments. One major focus is set on general basics as the type, manufacturer, serial number and geographic coordinates of the measured wind turbine. Valid operating conditions during the measuring period are restricted to only one setting, as alterations can influence the results. As example cleaning the blades during the measuring period is excluded. It is stated that used anemometer have to be calibrated according to MEASNET standard.

Power measuring devices must be capable of measuring the minimal power and maximal power but not more than 200 % rated power. Turbulent wind conditions are considered as a normalisation filter is defined. The standard distinguishes between three possible options as a completeness criterion for the wind speed range. In the test report a diagram of the power curve including the uncertainty is compulsory as well as a list of the used measuring points. As a final result, the annual energy production is estimated.

2.2.4 Measuring data from the field - Field Wind speed data versus field energy data

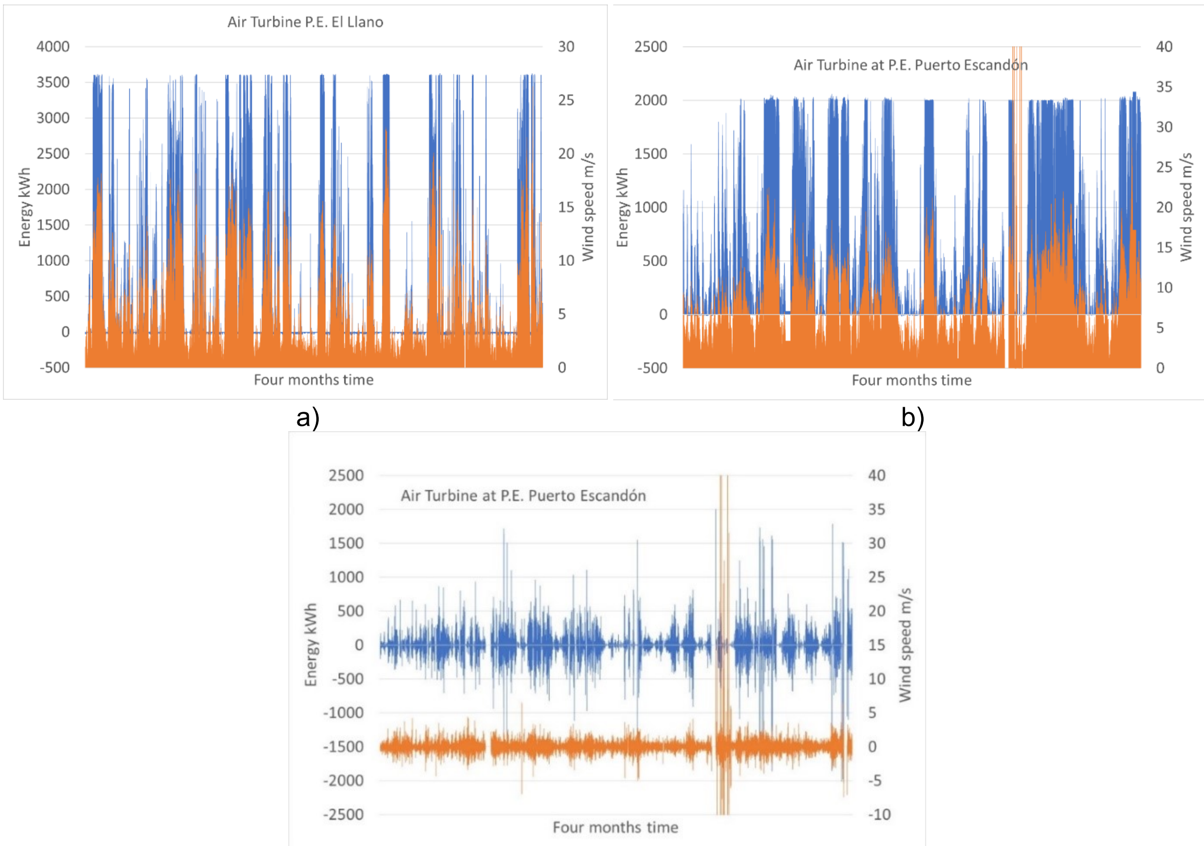
In these notes we present the field measurements relating the wind speed on wind turbines versus the actual electrical energy produced, in order to develop a Database to estimate the inputs to implement in NTBs for characterising the behaviour of wind turbines under real conditions.

Two Wind turbines were under study:

- A G90/2000 Siemens-Gamesa placed in Wind Farm Puerto Escandón (Teruel, Spain) and
- A V136 placed in Wind Farm El Llano (Zaragoza, Spain).

For both wind turbines, the data from 9 to 12 March 2020 approx. every ten minutes, which is a total of about 16 984 pairs of data consisting of wind speed and electrical energy generated. The considered data include the real stops intentionally carried out, so it reflects the real situation in the field. The negative data of energy are due to special situations where there is reactive power or low efficiency. This, however, is out of the scope of interest of this study.

DOI: 10.5281/zenodo.4733780



a) b)

c)

Figure 2: a) Wind turbine 1 in wind farm El Llano, energy (blue in kWh) and wind speed (orange in m/s) versus time, b) Wind turbine 2 in wind farm Puerto Escandón, energy and wind speed versus time, and c) Wind turbine 2 in wind farm Puerto Escandón, change in each variable in time ($y(t)$ - $y(t$ - 1)).

DOI: 10.5281/zenodo.4733780

When plotting the energy versus the wind speed, the form of the graphs (Figure 3a) and b)) is similar to the theoretical behaviour expected (Figure 3 c)):

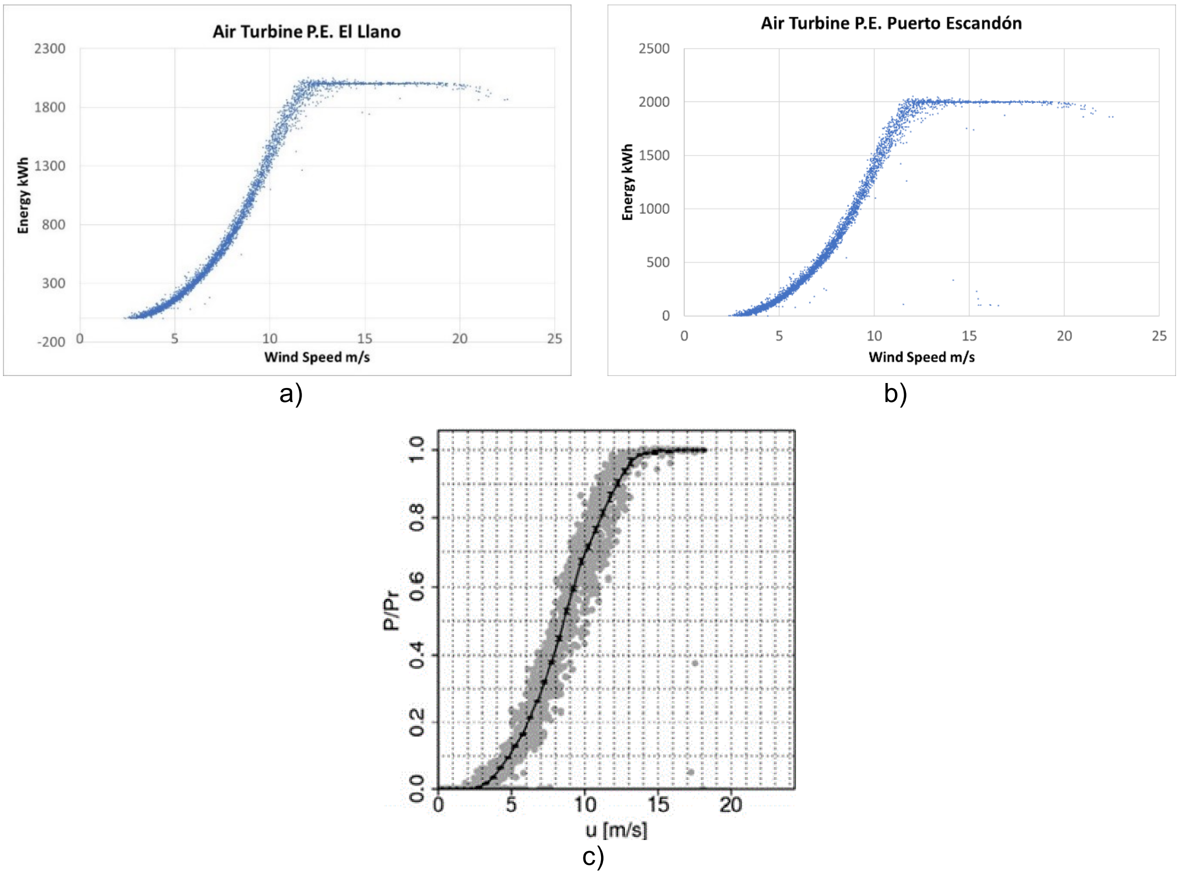


Figure 3: a) Wind turbine 1 in Wind farm El Llano, b) Wind turbine 2 in Wind farm Puerto Escandón, and c) theoretical behaviour expected [7].

The best approximation for the generated power is the second order polynomial as the following application in the wind turbine 2 in wind farm Puerto Escandón shows:

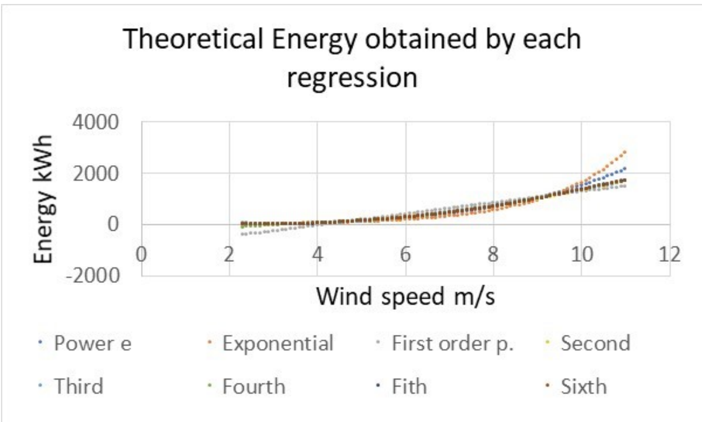
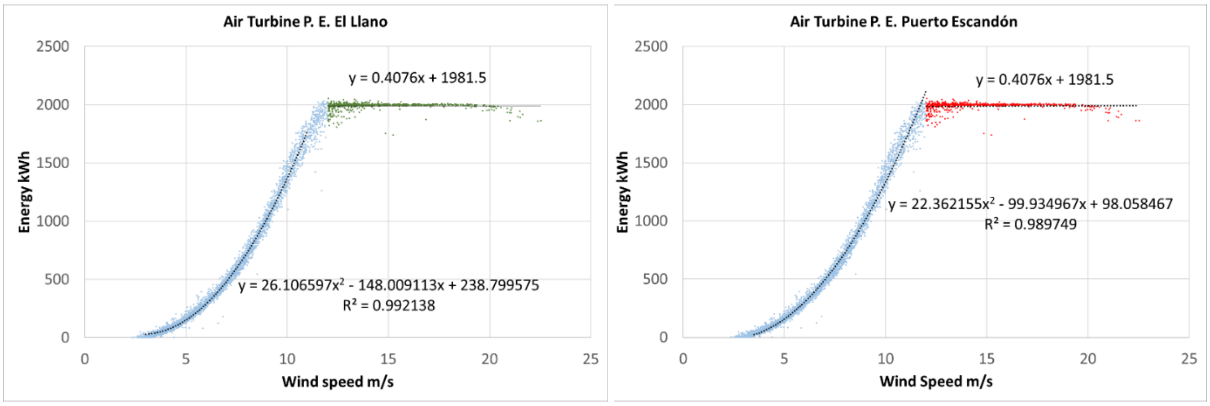


Figure 4: Graphical comparison of the possible regressions (wind turbine 2 in Wind farm Puerto Escandón.

Therefore, it has been found the **best real model** between the calibrated wind speed and the real electrical energy measured in two wind turbines:



a) b)

Figure 5: All regressions for a) wind turbine 1 in wind farm El Llano and b) wind turbine 2 in wind farm Puerto Escandón.

In this real model, we are developing statistical technics based on homocedasticity / heteroscedasticity analysis of the distribution of the data, in order to characterize the statistical distribution of each variable as good as possible. This will deal with an **uncertainty model** for wind speed and its propagation to the energy measured in real situations. We plan to relate the wind speed model with the torque as an input in the NTB model, and to be compared with the real energy model, through concatenated variable analysis.

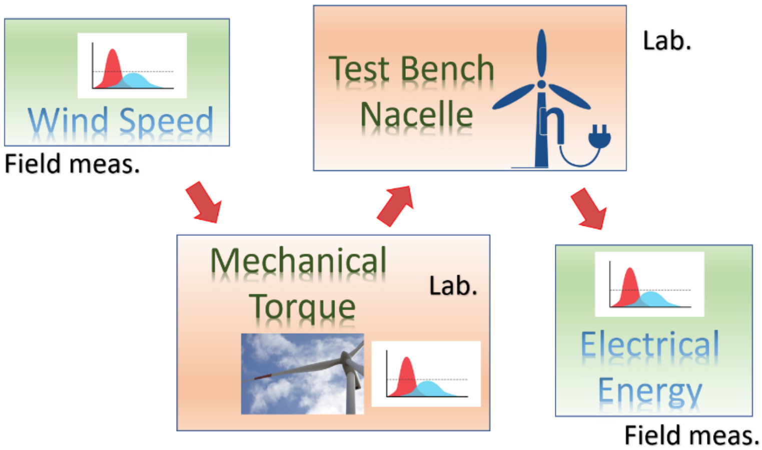


Figure 6: Work flow (Images from Pixabay: Markéta Machová, Robert Hell).

2.2.5 Comparison of the different methods

After reviewing the existing guidelines about efficiency measurement methods, it can be concluded that the differences are rather small. All methods refer to the IEC 61400-12-1 guideline and, therefore, meet the same criterions regarding electrical power measurement, wind speed measurement, and data collection and processing.

Regarding the efficiency measurement on test benches, the different guidelines offer valuable input regarding the power measurement accuracies. But as the guidelines describe field tests, the prime mover for the measurements is the wind speed which is not a controllable variable. A big number of factors have their influence in the exact determination of available energy (wind speed, terrain characteristics and roughness, direction, obstacles, air temperature, humidity, pressure, height, turbulences). So, power performance standards try to define the uncertainties of the wind speed measurement. Besides that, averaging periods of 10 minutes, requirements of quantities of data collected in certain wind speed bins and so on are used to minimise the uncertainty of the measurement of the power performance and of the efficiency of the turbine.

DOI: 10.5281/zenodo.4733780

In a test bench instead, the wind turbine starts after the blades at the rotor hub with controllable parameters of speed or torque. Therefore, the methods described in the guidelines cannot be transferred to the test bench. But as all the uncertainties related to the wind speed measurements lose their relevance, higher accuracy can be aimed. As in test benches conditions are reproducible, the measurement should not be as time consuming as described in the guidelines and no long period averaging should be required.

Translated to a test bench, where conditions are reproducible, ambient measurements should be performed, in order to guarantee that conditions of both the specimen and the measurement equipment are within a controlled range and no influence is verified in their performance and, consequently, in the efficiency values. The sampling frequency of the measurement system can be related to this specification, as conditions in a test bench are far more stable than in the field and variations in the behaviour of the specimen are not expected in faster rate.

In a test bench no **data rejection** is expected due to icing or contamination events. Measurement equipment is not expected to be affected and the possible affections on anemometers and blades are of no influence in a test bench.

The influence of **air density**, which is relevant in the case of field tests due to the amount of energy present in the wind will be of no influence for tests benches as well, and so the assessed differences between the site average density and the standard density (1.225 kg/m^3) when they exceed ± 0.15 kg/m^3 will not be considered as a source of additional uncertainty in the final report.

3 Efficiency measurement performed on a test bench

Test benches allow for reducing the time to market of innovations and can reduce costs in the development process. As the in-field measurements for an efficiency determination are time-consuming and not reproduceable, test bench measurements can be an improvement. In the following, two methods to measure the efficiency on a test bench are presented.

3.1 Calorimetric method

The calorimetric efficiency measurement method was performed at RWTH within the HybridDrive project [8]. An integrated drivetrain consisting of a two-stage planetary gearbox and a permanent magnet mid-speed synchronous generator with a rated power of 3 MW with an oil- and water-cooling system to regulate the temperatures in the drivetrain was measured. The method is based on the measurement of the heat losses in the drivetrain. This leads to a much higher measurement accuracy at high efficiencies.

As the losses are usually directly emitted into the environment mostly in form of heat, the device under test (DUT) needs to be isolated to make the heat loss measurable. The measuring of the flow rates and temperatures of inlet and outlet of the water- and oil-cooling circuit can be used to calculate the losses. However, as the high thermal inertia of the drivetrain is a heat sink, the DUT and the isolation have to reach stationary temperature characterising thermal state of the current operating point. In this state of thermal equilibrium, the heat loss and the heat conducted away in the cooling system are in the same quantity. For time efficient measurements, the approach is to start with small input powers and wait until a thermal equilibrium is reached until going to the next larger operational point. The results of the efficiency measurement as well as the measurement errors can be seen in the diagram in Figure 7.

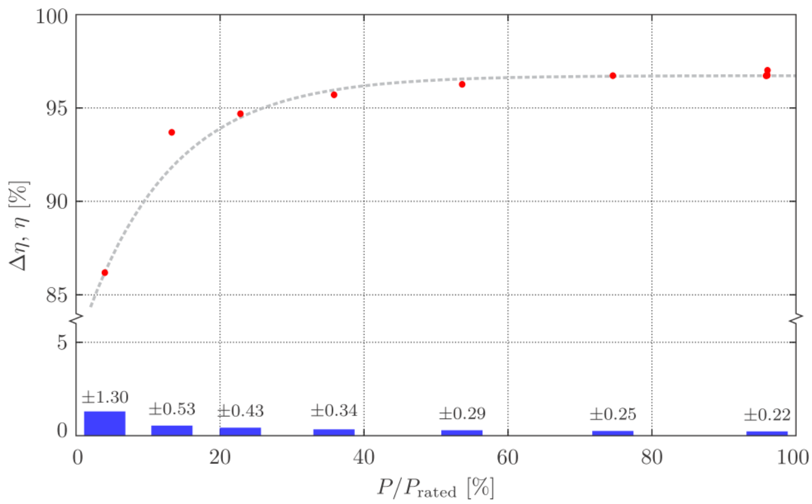


Figure 7: Measured efficiency over power with fitted curve. The vertical bars indicate the max. error [8]

The resulting uncertainties of the measurements below 0.5 % show that this method is feasible for efficiency determination for high efficiencies. However, the method is very time consuming because equilibrium temperatures needs to be achieved. Additionally, the effort to isolate an entire multi-megawatt nacelle to measure the heat loss is not appropriate. Also, the isolation cannot be perfect which is resulting in a measurement error that is difficult to quantify [8].

3.2 Alternative back-to-back efficiency determination method

Since common input torque measurement of the wind turbine drivetrain cannot satisfy the accuracy requirement of the efficiency determination, the new proposed method aims to reduce the influence of torque measurement on the accuracy of an efficiency determination. Instead of measuring the efficiency directly, the new method focuses on the measurement of power loss and in this way improves the accuracy of the efficiency determination considerably [9]. To measure the power loss of a certain operating point, the method requires a specially designed test procedure, where the drivetrain operates

 DOI: 10.5281/zenodo.4733780

first in the generator mode (Test A) and then in the motor mode (Test B). The power loss is obtained in comparing the mechanical and the electrical power measurement in the two operation modes.

Test A: The drivetrain operates in normal (generator) mode at a certain operation point. Mechanical and electrical power measurement are carried out on both sides of the drivetrain.

Test B: The drivetrain operates in the reversed (motor) mode at the same or similar operating point as in Test A. The rotating direction also must be reversed compared to in Test A, to make sure the torque measurement does not change the sign.

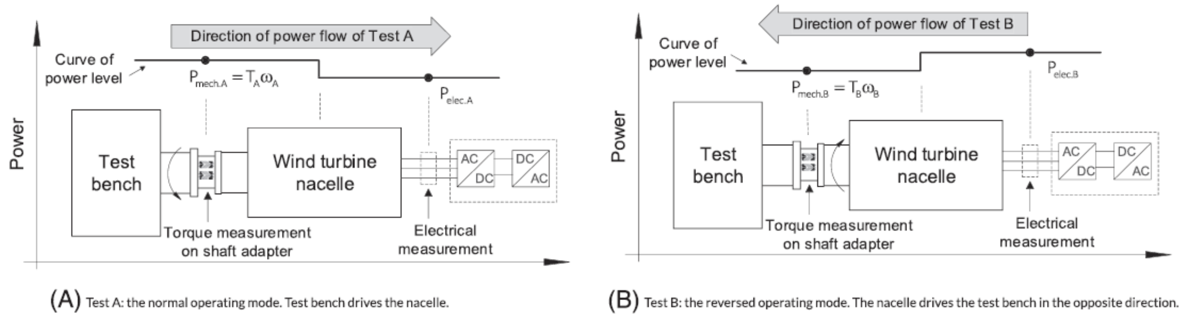


Figure 8: Test A and Test B required by the method [10].

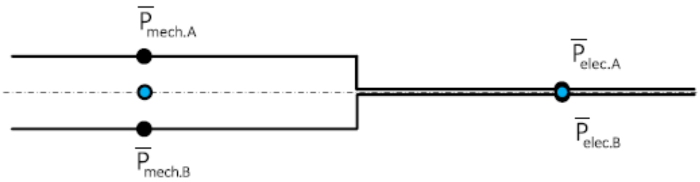


Figure 9: Power levels in Test A and Test B [10].

The total power loss in Test A and Test B can be obtained from the power measurement from both sides of the drivetrain:

$$\bar{P}_{\text{loss}} = (\bar{P}_{\text{mech.A}} - \bar{P}_{\text{mech.B}}) - (\bar{P}_{\text{elec.A}} - \bar{P}_{\text{elec.B}}) \tag{4}$$

Assume the power loss that happened in Test A takes a certain portion of the total power loss:

$$\bar{P}_{\text{loss.A}} = k_{\text{A}}\bar{P}_{\text{loss}} \tag{5}$$

where, k_{A} needs to be assumed through analysis against a certain amount of uncertainty.

The efficiency can be determined through this:

$$\eta_{\text{A}} = \bar{P}_{\text{elec.A}}/(\bar{P}_{\text{elec.A}} + \bar{P}_{\text{loss.A}}) \tag{6}$$

The proposed Alternative back-to-back test method for efficiency determination allows to measure the drive train efficiency of wind turbines without high accuracies on electrical and mechanical power measurements. The uncertainty of the measured drive train efficiency is lower than 1 %, while a decrease to under 0.5 % is considered possible. This represents a significant decrease compared to the conventional methods although using conventional measurement devices [9].

3.3 Comparison of the different methods

After reviewing the performed efficiency measurement methods on test benches, it can be concluded, that the accuracy of under 0.5 % is satisfying. But the efficiency measurements can only be performed for single operation points. As the persistent temperature has to be reached in every operation point, both measurement procedures are very time-consuming and costly. Furthermore, it is complicated to define the uncertainties of the methods and the methods are not traceable to national standards. Therefore the existing methods in their current form do not meet the demand of efficiency measurement on test benches. Further development and validation would be needed to address the shortcomings pointed out above.

DOI: 10.5281/zenodo.4733780

4 Data synchronisation

For an accurate efficiency determination of wind turbines, the mechanical and electrical power should be measured at the same time or, in practice, with low timewise misalignment. In regular electric machine test benches in the kilowatt range, the mechanical and electrical power are usually measured with one DAQ system, such as a power analyser, in which the data are measured in optimal timewise alignment with internal synchronization. In NTBs on the contrary, multiple frequency inverters are connected in parallel to generate the power in the multi-megawatt range, which results in as many as 100 channels; and therefore, different DAQ systems are needed. Particularly in this project, the mechanical transfer standard with independent DAQ system should be synchronised with the built-in measuring systems in the NTB. As a consequence, the timewise synchronisation of independent DAQ systems must be investigated to ascertain the most suitable systems for the usage in NTBs considering the application of measuring systems and evaluations that require a high data alignment accuracy in a timewise manner.

4.1 Synchronisation mechanism

In this subsection, the basic principles and the existing technologies for data synchronisation of independent DAQ systems are presented.

The precision time protocol (PTPv2) is a commonly used time synchronisation communication protocol to synchronise clocks of different DAQ systems. In this protocol, one master device is connected to other slave devices through ethernet. Figure 10 shows the delay request-response between the master and the slave. Firstly, a Sync massage is sent from the master to the slave with time stamp t_1. The slave receives the Sync massage at t_2 and sends back a Delay_Req signal to the master at t_3, which is received by the master at t_4. In this process, t_1 and t_4 are stamped according to the master clock while t_2 and t_3 are stamped according to the slave clock. The values of t_1 and t_4 are send to the slave in the Follow_Up and Delay_Resp messages, so that the slaves can calculate the time difference Δt between their local clock and the master clock with equation (7) and synchronise their local clocks.

$$\Delta t = \frac{(t_2 - t_1) + (t_4 - t_3)}{2} \tag{7}$$

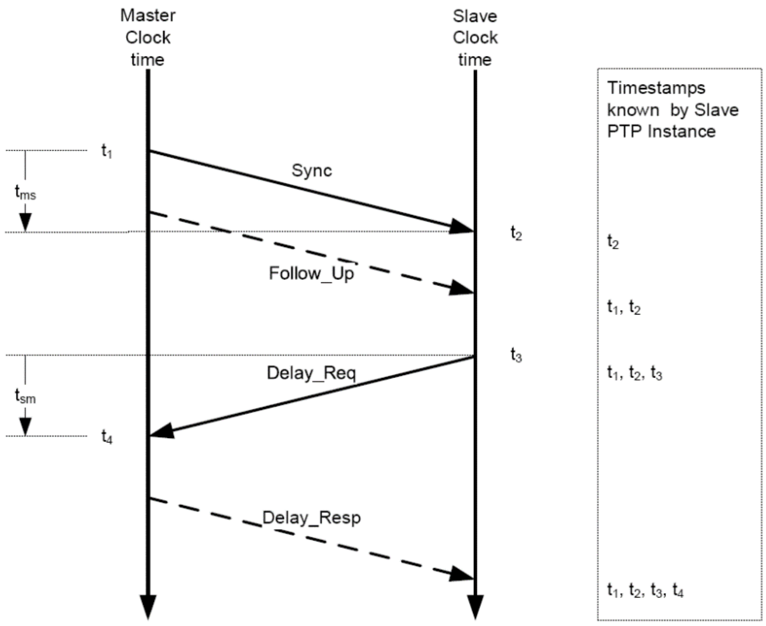


Figure 10: Delay request-response in PTPv2 for time synchronization [11].

Besides PTPv2, there are many other time synchronisation mechanisms based on similar principles. An overview of the commonly used synchronisation mechanisms is presented in Table 1.

Table 1: Overview of the commonly used synchronisation mechanisms.

Synchronisation mechanisms	Ethernet (NTP)	Ethernet (PTPv2)	IRIG-B	EtherCAT	IEEE1394b FireWire
Accuracy [12]	1 ms to 50 ms	< 1 µs	< 1 ms to 100 ns	< 1 µs	< 1 µs
Wireless Connection	Possible	Possible [13]	Possible [14]	n/a	n/a

4.2 Accuracy requirement on synchronisation in NTBs

In NTBs, the efficiency of wind turbines η is determined by measuring the electrical power P_e and the mechanical power P_m:

$$\eta = \frac{P_\mathrm{e}}{P_\mathrm{m}}. \tag{8}$$

For the electrical power[1] calculation, the product of current $u(t)$ and voltage $i(t)$ is averaged over a time interval T_e, which should ideally be chosen as an integer multiple of the signal period:

$$P_\mathrm{e} = \frac{1}{T_\mathrm{e}} \int_0^{T_\mathrm{e}} u(t) \cdot i(t) dt. \tag{9}$$

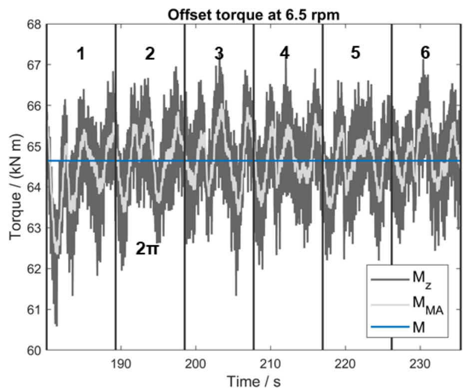
And the mechanical power is averaged over the time interval T_m, which is, for an efficiency calculation, ideally of the same length as T_e:

$$P_\mathrm{m} = \frac{1}{T_\mathrm{m}} \cdot \int_0^{T_\mathrm{m}} M(t) \cdot n(t) \mathrm{d}t \tag{10}$$

Since the shaft rotates at a speed $n(t)$ near to constant, it can be averaged separately from the torque $M(t)$:

$$P_\mathrm{m} = \frac{1}{T_\mathrm{m}} \cdot \int_0^{T_\mathrm{m}} M(t) \mathrm{d}t \cdot \int_0^{T_\mathrm{m}} n(t) \mathrm{d}t \tag{11}$$

An example of measured torque signal in an NTB is presented in Figure 11. It can be observed that the influence on the torque signal is periodically recurrent. Therefore, torque should always be averaged over an integer number of revolutions (min. two revolutions) and the data recording time T_m varies with the rotational speed.



- M_z (dark grey) is the raw torque signal measured by the torque transfer standard installed in the NTB.
- M_{MA} (light grey) is the moving average of the raw signal with a window size of 50 data points.
- M (blue) is the mean torque value averaged over 6 full revolutions.

$M_{\mathrm{rev}=1} = 64.314\ kN\ m$ $\quad M_{\mathrm{rev}=4} = 64.702\ kN\ m$

$M_{\mathrm{rev}=2} = 64.723\ kN\ m$ $\quad M_{\mathrm{rev}=5} = 64.583\ kN\ m$

$M_{\mathrm{rev}=3} = 64.744\ kN\ m$ $\quad M_{\mathrm{rev}=6} = 64.793\ kN\ m$

Figure 11: Measured torque signal in an NTB at 6.5 rpm.

For a valid efficiency determination, T_e should be set equal to T_m and aligned synchronously in a timewise manner. The synchronisation can be evaluated by the ratio k between time synchronisation accuracy a_s and the length of the averaging interval.

[1] For simplification, the calculated electrical power is shown assuming a single-phase system.

DOI: 10.5281/zenodo.4733780

$$k = \frac{a_\mathrm{s}}{T_\mathrm{m}} \tag{12}$$

In the worst-case scenario, the low speed shaft rotates at 20 min^{-1} maximum speed and the signals are averaged over the minimum number of revolutions: two revolutions. In this scenario, we have the shortest $T_\mathrm{m} = 6\ s$ and, therefore, the worst ratio *k*. The ratio *k* with different synchronisation mechanisms is calculated in Table 2 based on their synchronisation accuracy. It is safe to conclude that all the listed synchronisation mechanisms are able to offer a high data alignment accuracy in a timewise manner.

Table 2: Ratio *k* by commonly used synchronisation mechanisms in worst-case scenario.

Synchronisation mechanisms	Ethernet (NTP)	Ethernet (PTPv2)	IRIG-B	EtherCAT	IEEE1394b FireWire
k	$1.6{\cdot}10^{-4}$ to $8x10^{-3}$	< $1.6x10^{-7}$	< $1.6x10^{-4}$ to $1.6x10^{-8}$	< $1.6x10^{-7}$	< $1.6x10^{-7}$

4.3 Synchronisation topology at Fraunhofer IWES

In the NTB at Fraunhofer IWES, the GPS time received by the GPS sensor is set as the master clock for all DAQ systems in the NTB. After conversion, the synchronisation is available as NTP or IRIG-B signals. The synchronisation signals can be directly connected to the DAQ systems in static. Via a slip ring (for IRIG-B) and WLAN (for NTP), the DAQ systems mounted on the rotating shaft can be reached as well (Figure 12).

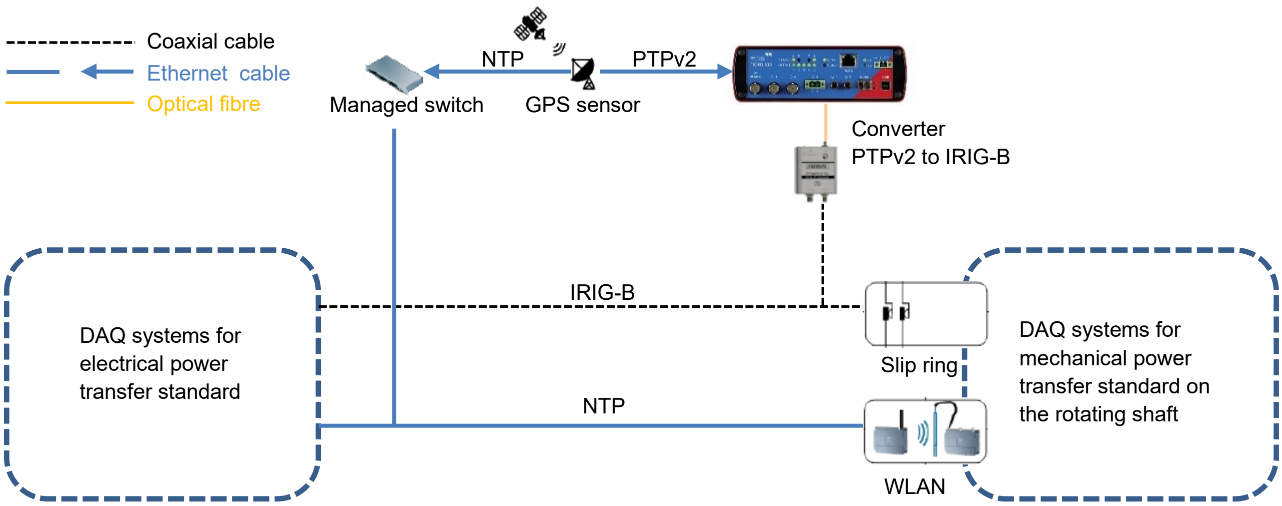


Figure 12: Timewise synchronisation topology diagramm at Fraunhofer IWES.

5 Data transmission technologies

While implementing a measurement system for wind turbines, data transmission is of high importance. The major challenge is to transfer the measured mechanical power from the rotation shaft to the static measuring system wirelessly. Therefor the state-of-the-art in data transmission technologies is carried out in this chapter with focus on the amount of data that can be transmitted and the susceptibility to errors during data transmission. This will serve the following technical WPs as a basis to design the measuring system.

5.1 Short distance – Slip ring technologies

A slip ring is an assembly for transmitting data and power across a rotating connection as depicted in Figure 13. The growing need for faster and more reliable data transmission between rotating components in modern industrial scenarios imposes strict requirements on bandwidth, crosstalk and electromagnetic interference (EMI) performance of the data interfaces used in slip rings. Meeting these requirements is essential to guarantee real-time operation, continuous uptime, and maximum efficiency of the corresponding industrial equipment. [15]

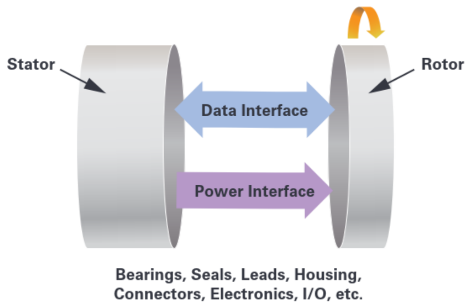


Figure 13: Slip ring - high level block diagram. [15]

Industrial rotary data interface assemblies must ensure constant transmission quality at very fast rotational speeds at rates of typically 100 Mbps. Industrial applications also call for support of industrial bus protocols, as well as deterministic real-time communication, to permit time sensitive applications and Internet of Things (IoT) functionality. Data interface solutions designed for these applications must be immune to physical misalignments, EMIs and crosstalk to enable error-free data transmission with bit error rates (BER) of 1×10^{-12} or better. Contaminants present in the industrial environment should not affect the operation of a slip ring that ideally must be maintenance-free and not suffer from wear. There are different types of slip rings that vary in terms of their functional features, form factor, rotational speeds (rpm), maximum data rate, power ranges, type of supported interfaces, channel count and many other design aspects shaped by application requirements. Data communication technologies used to realise this function can generally be classified into contacting and contactless slip rings. They abound with many variations depending on the type of coupling they utilise in order to realise a communication channel for data transmission. Table 3 offers numerous sets of features and capabilities that can meet typical requirements of industrial slip ring applications. However, most of these conventional technologies are effective for data transmission only over short distances, which requires transceiver elements on a rotor and a stator to be in very close proximity to each other. [15]

DOI: 10.5281/zenodo.4733780

Table 3: Classification of slip rings based on data interface coupling technologies. [15]

Type		Features	
Contacting	Composite brushes	High currents, high rpm, low data rates	Contact wear, EMI, channel bandwidth, resistance variation
	Monofilament wires	Low currents, low noise, low contact resistance	
	Polyfilament wires	Multiple contacts per channel, minimal noise, minimal contact resistance, high data rates	
Contactless	FORJ	EMI-free, Gbps-level data rates, strong losses, sensitive to misalignments, require protection	
	Inductive	Near-field, magnetic field coupling, high rpm, high power	
	Capacitive	Near-field, electric field coupling, low cost, light weight, less sensitive to misalignments, high rpm, Gbps-level data rates	

5.1.1 Contact-type interfaces

Contact-type solutions typically rely on composite, monofilament or polyfilament brushes on a stator that slide against conducting rings on a rotor, thereby creating an uninterrupted passage of electrical signals between moving and stationary components as depicted in Figure 14. The selection of brush type regarding data communication depends on the signal bandwidth, data transfer rate, required transmission quality, operational currents and rpm. Although this is a well-established technology that has been employed in slip rings since their invention, it has certain limitations. Reliability of contact-type slip rings suffers in harsh operating environments due to the presence of mechanical contacts requiring regular maintenance. Electromechanical rotary joints are also prone to EMI. In addition to that, the characteristics of the physical media used to establish the contact interface, as well as various mismatch effects, have a strong impact on the channel bandwidth. Moreover, sliding contacts generate electrical resistance variation that degrades the transmission quality, which can be especially critical in high rate real-time applications. [15]

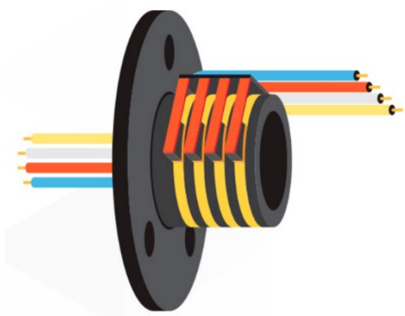


Figure 14: Contact-type slip ring. [15]

The brushes come in several configurations as well, but the three primary ones are shown in Figure 15. The brush selection criteria include size, power requirements, ring configuration, and service life requirements. A limit to rotation speed at which a slip ring can operate depends on the slip ring type. Some models can operate up to 20 000 min^{-1}, but the typical limit on operating speed is about 250 min^{-1} to 1000 min^{-1}although this can vary depending on several parameters such as size, materials and environment. Sliding contacts produce resistive noise during rotation which is the result of a slight variation in contact resistance, typically about 10 mΩ to 20 mΩ. This resistance variation value produces a low-level voltage variation on an electrical signal. For low-noise power circuits and low-level analogue signals, special design materials and considerations can produce even lower levels of contact noise. The limitation on slip ring power levels result from physical size constraints. High power requires space for additional insulation (voltage) and large conductors (current). Slip rings produce voltage levels up to

25 kV with current ratings that exceed 1000 A. Contact-type slip rings can achieve serial data rates up to about 1.25 Gbps. [15]

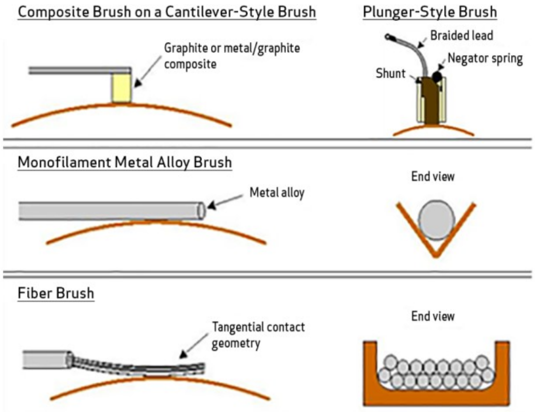


Figure 15: Three primary contact brush configurations. [16]

5.1.2 Contactless interfaces

Contactless slip rings overcome those limitations by using radiating or non-radiating electromagnetic fields to transfer the data across rotating parts. This technology offers several performance advantages over electrical signal transmission. The lack of mechanical contacts avoids contact wear requiring less maintenance and does not suffer from data loss arising from resistance at high rotational speeds. [15]

5.1.2.1 *Inductive and capacitive interfaces*

Another type of contactless technology is based on near field coupling mechanisms realised through electric and magnetic fields generated by primarily non-radiating inductive and capacitive circuit elements in lower frequency bands of the electromagnetic spectrum. Wireless slip rings are considered an upgrade to traditional slip rings, as their lack of standard mechanical rotating parts means they are typically more resilient in harsh operating environments and require less maintenance. [15]

Inductive methods apply the principle of electromagnetic induction to interface moving parts of an assembly. Slip rings using this type of coupling, which is schematically depicted in Figure 16, are useful for industrial applications with high rotational speeds but they are more suitable for the transmission of power rather than for the transmission of high speed data. However, the power between coils that can be transmitted is limited. Typically, a traditional contact-type slip ring transmits orders of magnitude more power in the same volume. Inductive power supply can also be used. Using a stationary inductive head and a receiver coil on the rotating component, the supply voltage for telemetry is transmitted without contact. [15]

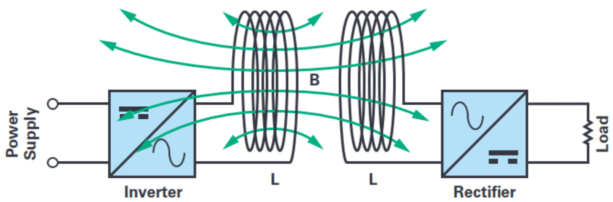


Figure 16: Inductive coupling. [15]

In contrast to inductive slip rings relying on a magnetic field, the slip rings based on capacitive technology use electric fields to transfer data between a rotor and a stator. The capacitive coupling method shown in Figure 17 offers the realisation of a relatively low cost and lightweight solution with negligible eddy current losses and excellent misalignment performance. This technology enables reliable data transmission at high speeds of several Gbps in harsh operational environments and independent of

 DOI: 10.5281/zenodo.4733780

rotational speeds. Capacitive slip rings are often designed for a combination with Ethernet fieldbuses and they are broadly used in time sensitive industrial applications. [15]

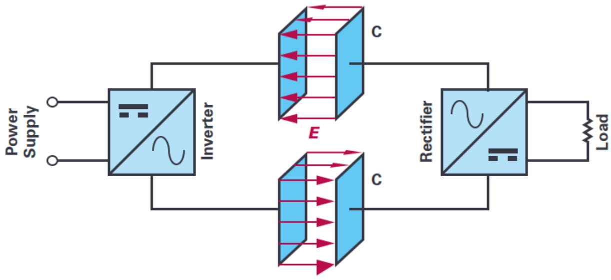


Figure 17: Capacitive coupling. [15]

5.1.2.2 ***Fibre optic rotary joints***

The most common example of a contactless solution is a fibre optic slip ring known as a fibre optic rotary joint (FORJ), which is schematically shown in Figure 18. A FORJ is the optical equivalent to an electrical slip ring and is often used in conjunction with slip rings. FORJs come in single- and multi-channel versions and have practically unlimited bandwidth. They are limited in number of physical channel but time division and wave division multiplexing significantly expands the number of channels. FORJs rely on optical radiation to transfer data and operate typically at infrared wavelengths between 850 nm and 1550 nm allowing EMI-free transmission of every kind of analogue or digital optical signal at very high data rates of several dozens of Gbps. However, fibre optic solutions are not without challenges. They experience strong extrinsic losses that result in signal attenuation caused by angular and axial misalignments. These misalignments are also the main contributor to rotational signal fluctuations that can be critical in some applications. Moreover, FORJs usually require high levels of protection in harsh industrial environments. [15], [17] and [18]

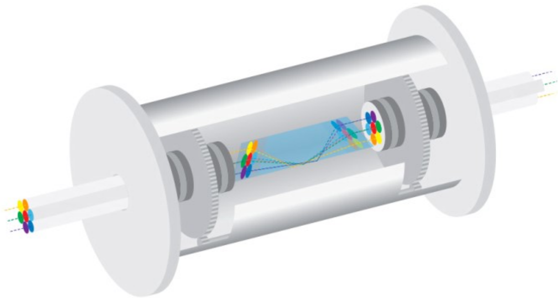


Figure 18: Fibre optic rotary joint [15].

FORJs can be divided into classes based on number of passes and mode of operation: single- or multi-pass and passive or active. Passive FORJs transmit an optical signal from the rotating to stationary structure without any electronic processing although components such as filters and lenses can be used to process the optical signal. Active FORJs incorporate electronics to process the signal to improve rotor and stator transmission properties and can involve electrical / optical conversion, amplification, signal conditioning and re-clocking. Active devices are used primarily with applications requiring a through-bore. Active FORJ devices tend to be customised for specific applications. Passive FORJs have become standard catalogue devices and have found uses in widespread applications. [18]

5.2 Short-to-medium distance – Radio technologies

The following data transmission technologies are commonly used in short-to-medium distances (wireless local area network, wireless personal area network) in NTBs.

Table 4: Comparison of short-to-medium distance data transmission technologies [19].

Technology	WLAN – IEEE 802.11ax	Bluetooth (LE)
Data rate (max.)	< 10 Gbit/s	2 Mbit/s
Transmission distance (max.)	< 200 m	< 100 m
Frequency band	2.4 GHz, 5 GHz, 6 GHz	2.4 GHz

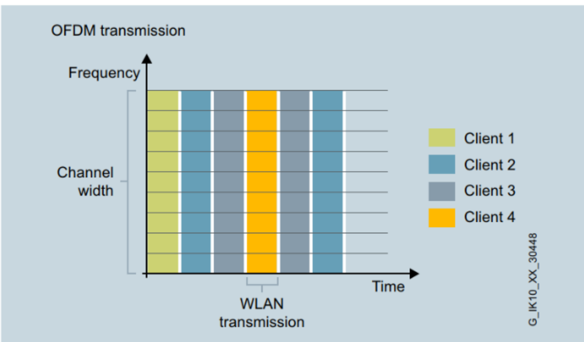
5.2.1 Industrial WLAN – IEEE 802.11ax

In many existing NTBs the wireless local area network standard is used for data transmission from rotating components to static ones. WLAN is a family of radio technologies commonly used for wireless local area networking of devices. It is based on the IEEE 802.11 family of standards. Compatible devices can connect to each other over Wi-Fi through a wireless Access Point as well as to connect Ethernet devices and may use it to access the Internet. Such an Access Point has a range of about 20 m indoors and a greater range outdoors. Access Point coverage can be as small as a single room with walls that block radio waves, or as large as many square kilometres achieved by using multiple overlapping access points. The different versions of WLAN are specified by various IEEE 802.11 protocol standards, with the different radio technologies determining the ranges, radio bands, and speeds that may be achieved. WLAN most commonly uses the 2.4 GHz ultra-high frequency (UHF) and the 5 GHz super-high frequency (SHF), and industrial, scientific and medical (ISM) radio bands; these bands are subdivided into multiple channels. Each channel can be time-shared by multiple networks. These wavelengths work best for line-of-sight. Many common materials absorb or reflect them, which further restricts range, but can tend to help minimise interference between different networks in crowded environments. At close range, some versions of WLAN, running on suitable hardware, can achieve speeds of over 1 Gbps. In the following chapters the major changes of the new IEEE 802.11ax standard are presented.

5.2.1.1 *OFDMA uplink & downlink*

With the uplink/downlink orthogonal frequency-division multiple access (OFDMA) technology, more data can flow simultaneously, resulting in more efficient transmissions. It increases efficiency and reduces latency as several devices communicating concurrently in portions of the frequency spectrum allocated proportional to their needs. By using OFDMA modulation, WLAN becomes a much better solution for Access Points, service provider WLAN and for WLAN/LTE aggregation.

Previous WLAN standards utilises orthogonal frequency-division multiplexing (OFDM) for the data transmission. With OFDM, only one participant can communicate at a given time. The communication channel is fully used during the data transmission as depicted in Figure 19. With IEEE 802.11ax, OFDMA is introduced for the data transmission. A communication channel is divided into up to nine sub-channels, so-called resource units. Sub-channels can be distributed to different users so that they can communicate at the same time as depicted in Figure 19. OFDMA enables serving of multiple users in less time, efficient transmission of small data packets, and a better way to implement quality of service mechanisms. OFDMA by itself is not enough for executing critical automation tasks. By developing a polling mechanism based on OFDMA, it will be possible for industrial applications to achieve low latencies permanently at an Access Point in pure IEEE 802.11ax environments. [20]



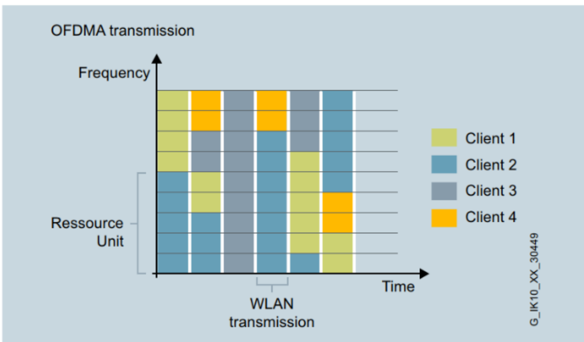


Figure 19: OFDM communication OFDMA communication. [20]

DOI: 10.5281/zenodo.4733780

5.2.1.2 *Target wake time (TWT)*

Orchestrate specific times when clients awake / sleep and reduces access contention by allowing devices to wake up at periods other than the beacon transmission period. By using TWT power consumption is reduced and battery life of the device is improved [21]. IEEE 802.11ax extends the mechanisms for energy saving and makes them more efficient. TWT enables trigger-based data transmission. The Industrial WLAN clients can now *go to sleep* between sending and receiving packets and only wake up at an agreed time if necessary, after many hours in order to resume data transmission. There are different options for using the mechanism as energy-saving and flexible as possible as depicted in Figure 20. In individual TWT the time for the next transmission is exclusively agreed between Access Point and client. In broadcast TWT the time for the next (multicast) transmission is specified by the Access Point. In opportunistic power save the client reacts to the data packets of the Access Point and no fixed time interval is negotiated. These features bring several advantages for industrial applications, including longer runtime of battery-powered applications. [20]

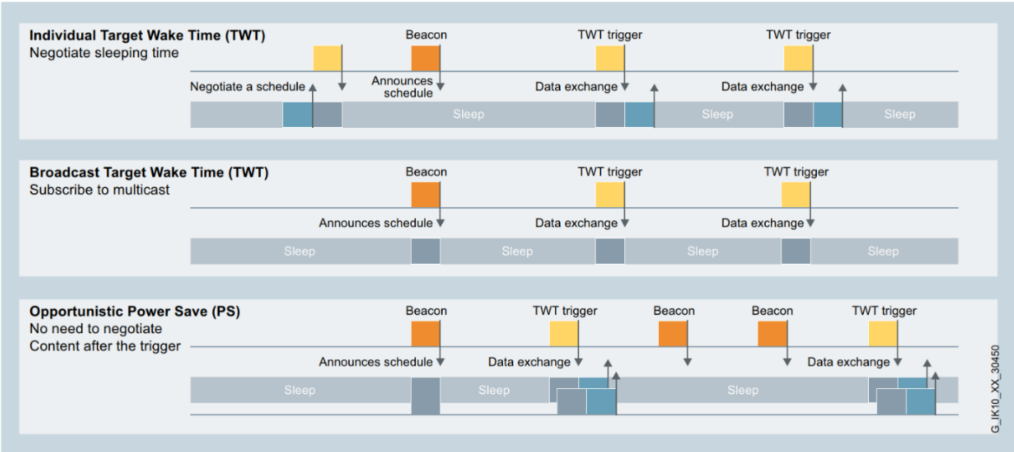


Figure 20: Target Wake Time (TWT) [20].

5.2.1.3 *Spatial reuse*

Spatial reuse enables devices to differentiate transmission in their own network from transmissions in neighbouring networks. It allows Access Points to share channel capacity more efficiently. By spatial reusing collision between communications of nearby users is mitigated. WLAN as a shared medium with a varying number of channels in the 2.4 GHz and 5 GHz bands always requires a good planning of the installation. The objective of this frequency planning is, among other things, to prevent or at least minimise effects due to overlapping channels of the same frequency. The results are referred to as co-channel interference (CCI). With the so-called spatial reuse by means of the basic service set (BSS) colouring, the standard wants to enable the reuse of channels, even if they are relatively close together locally, which would normally lead to strong interference. For this purpose, a *colour* (de facto a number) is assigned to the BSS of an Access Point. With this colour assignment, the users can communicate even if the channel is actually occupied by users of a different colour provided that they are not transmitting too strongly on the channel. Spatial reuse as a technology is newly defined in the standard. In theory, it enables a considerably more efficient use of the spectrum and new paradigms when planning facilities. The following advantages can be achieved in industrial applications: easier coordination between different equipment suppliers in a factory and in industrial IoT environments, and a better distribution of the clients to different, interference-free Access Points. [20]

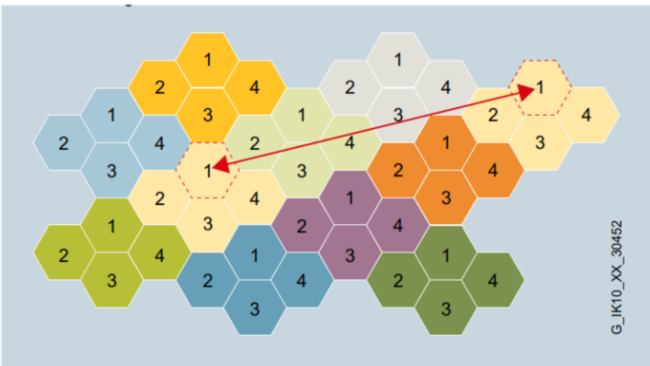


Figure 21: BSS colouring [20].

5.2.2 Bluetooth (LE)

The Bluetooth low energy (LE) radio is designed for very low power operation. To enable reliable operation in the 2.4 GHz frequency band, it leverages a robust frequency hopping spread spectrum approach that transmits data over 40 channels. The Bluetooth LE radio provides flexibility including multiple physical layer options that support data rates from 125 kbit/s to 2 Mbit/s, multiple power levels, from 1 mW to 100 mW, as well as multiple security options up to government grade. Bluetooth LE also supports multiple network topologies, including point-to-point, broadcast and mesh networking. [19]

DOI: 10.5281/zenodo.4733780

6 Standards for the efficiency determination of electrical machines

Electrical machines with or without variable-speed drives are used for different field of applications (wind energy, traction, robotics, aerospace, electric vehicles, etc.). The overall information of the International Electrotechnical Commission (IEC) or European (EN) standards regarding the efficiency measurement of electrical machines are summarised in this section.

6.1 IEC standards for electrical machines which are relevant for efficiency determination of electrical machine

Three phase electrical machines comply with the following IEC or EN standards consisting of information required for efficiency determinations of electrical machine are listed in Table 5.

Table 5: IEC/EN standards for electrical machines [22].

IEC/EN standards	Title
IEC 60034-1	Rotating electrical machines – Part 1: Rating and performance
IEC 60034-2-1	Rotating electrical machines – Part 2-1: Standard methods for determining losses and efficiency from tests (excluding machines for traction vehicles)
IEC 60034-2-2	Specific methods for determining separate losses of large machines from tests Supplement to IEC 60034-2-1
IEC 60034-4-1	Rotating electrical machines – Part 4-1: Methods for determining electrically excited synchronous machine quantities from tests
IEC 60034-5	Rotating electrical machines – Part 5: Degrees of protection provided by the integral design of rotating electrical machines (IP code) – Classification
IEC 60034-6	Rotating electrical machines – Part 6: Methods of cooling (IC Code)
IEC 60034-7	Rotating electrical machines – Part 7: Classification of types of construction, mounting arrangements and terminal box position
IEC 60034-8	Rotating electrical machines – Part 8: Terminal markings and direction of rotation
IEC 60034-9	Rotating electrical machines – Part 9: Noise limits
EN ISO 1680	Acoustics - Test code for the measurement of airborne noise emitted by rotating electrical machines
IEC 60034-11	Rotating electrical machines – Part 11: Thermal protection
IEC 60034-12	Rotating electrical machines – Part 12: Starting performance of single-speed three-phase cage induction motors
IEC 60034-14	Rotating electrical machines – Part 14: Mechanical vibration of certain machines with shaft heights 56 mm and higher – Measurement, evaluation and limits of vibration severity
IEC 60034-18-1	Rotating electrical machines – Part 18-1: Functional evaluation of insulation systems – General guidelines
IEC 60034-30-1	Rotating electrical machines – Part 30-1: Efficiency classes of line operated AC motors
IEC 60038	IEC standard voltages
IEC 60072–1	Dimensions and output series for rotating electrical machines – Part 1: Frame numbers 56 to 400 and flange numbers 55 to 1080
IEC 60085	Electrical insulation – Thermal evaluation and designation
IEC 61800-9-2	Adjustable speed electrical power drive systems – Part 9-2: Ecodesign for power drive systems, motor starters, power electronics and their driven applications - Energy efficiency indicators for power drive systems and motor starters

The low-voltage three-phase, single-speed line-operated (50 Hz and 60 Hz) AC motors with numbers of poles less than 8 and output power up to 1000 kW are classified according to IEC 60034-30-1 [23] standards as shown in Table 6. However, this standard IEC 60034-30-1 does not include the inverter-driven motors that cannot be operated directly from the mains. In addition, inverter fed permanent magnet synchronous machines (PMSMs) and a synchronous reluctance motors (SynRMs) are normally expressed as efficiency class IE4 as described in IEC 60034-30-1.

Table 6: IEC / EN for efficiency classes of line operated AC motors (IE code) IEC 60034-30-1 [23].

IEC efficiency classifications class codes			
IE1: Standard efficiency	IE2: High efficiency	IE3: Premium efficiency	IE4: Super-premium efficiency

6.2 Global review of international and national standards regarding efficiency determination of electrical machines

International standards regarding the efficiency of electrical machines in the EU, the USA, Canada, Japan and Russia have been analysed and discussed for induction motors (asynchronous machines (ASMs)) and presented in these papers [24] and [25]. The different national and international standards bodies for efficiency of electrical machines are shown in Table 7. Each national and international standard has its proper definitions and ways of determining the efficiency of electrical machines. Most of the standards have similar information which depends on the type of test and vocabulary used to describe the results. The primary difference for ASMs among these standards is the test methods that is used to find the stray load losses.

Table 7: Standards regarding efficiency determination of electrical machines.

National and international standards	Address an issue	Title of standard	Remarks
IEC 60034-1:2017 [26]	Rating and performance	Rating and performance	All rotating electrical machines
IEC 60034-2-1:2014 [27]		Standard methods for determining losses and efficiency from tests (excluding machines for traction vehicles)	AC, DC, synchronous machines
IEC 60034-2-2:2010 [28]		Specific methods for determining separate losses of large machines from tests- Supplement to IEC 60034-2-1	Special and large motors
IEC 60034-2-3:2013 [29]	Test for losses and efficiency	Specific test methods for determining losses and efficiency of converter-fed AC induction motors	Converter-fed motors
Institution of Electrical and Electronic Engineers (IEEE) IEEE 112:2017 [30]		IEEE Standard Test Procedure for Polyphase Induction Motors and Generators	IEEE 112-B uses loss segregation
British Standards (BS) BS-269		Rules for methods of declaring efficiency of electrical machinery	Similar to IEC 60034-2-1
USA: Department of Energy (DOE) 10 CFR Part 431 and National Electrical Manufacturers Association (NEMA) MG 1		Motors and Generator	IEEE 112-B is accepted by Both DOE and NEMA MG 1

DOI: 10.5281/zenodo.4733780

Canadian Standards Association (CSA) C390-10 [31]		Test methods, marking requirements, and energy efficiency levels for three-phase induction motors	A very similar procedure to the IEEE112-B Standard
IEC 60034-30-1 [23]	Efficiency classes	Efficiency classes of single speed, three-phase, cage induction motors (IE-code)	Induction motors 0.75 kW to 375 kW, 2-, 4-, 6-pole with 50 Hz and 60 Hz

Note: Similar regulations in many other countries, e.g. the Pan American Standard Commission (COPANT), the Japanese Electrotechnical Commission (JEC 37), South Korea, China, Australia, New Zealand, etc. are available for different test methods for the determination of the motor efficiency.

7 Principles of direct and indirect efficiency measurement methods

The brief background information of efficiency measurement in electrical machines is discussed in this section. The direct efficiency measurement of electrical machines is based on electrical and mechanical power, i.e., input/output measurements. Whereas the indirect efficiency measurement of electrical machines is based on electrical power and power losses measurements, i.e., summation of losses. The indirect efficiency measurement method mainly focuses on separation of the individual losses using different tests. The losses and the efficiency of electrical machines need to be conserved in all the electrical machines.

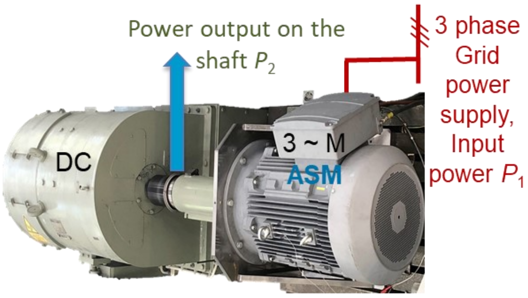
7.1 Efficiency determination for induction motors

The international standard IEC 60034-2-1 [27] explains the test methods for the determination of losses and the efficiency classification which generally focuses on test methods for induction motors, synchronous machines (field excited machines) and DC machines. Similarly, the efficiency classification (IE-Code) of AC motors is presented in IEC 60034-30-1 [23]. The IEEE 112-B [30] also presents the test procedure for polyphase induction motors and generators similar to IEC 60034-2-1 [27]. The comparison analysis of IEC 60034-2-1 and IEEE 112B is presented in [32] and [33].

7.1.1 Direct efficiency determination for induction motors

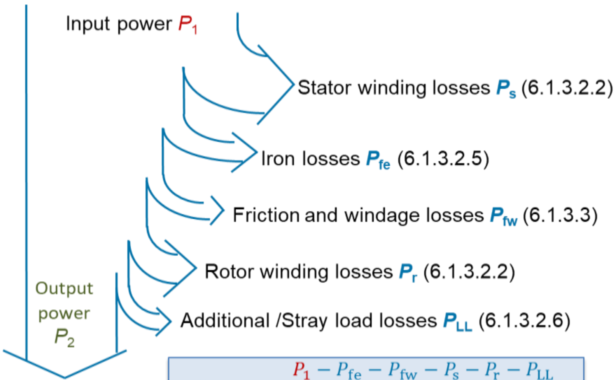
In general, the direct efficiency ($\eta_{\mathrm{d,Motor}}$) of induction motors is determined by the ratio of the measured output power to the input power. This method of determining the efficiency of the machine is known as the direct efficiency measurement method (IEC/EN 60034-2-1) and represented as shown in Figure 22a). This method is simple and easy to use. Due to the high efficiency of currently manufactured electrical machines (e.g. 95 %), the power loss (Figure 22b)) is very small in relation to the electrical and mechanical power. Using this method, even small MUs including offset errors in the torque measurement thus have a major influence on the power loss and the measured variable efficiency. The mechanical output power, $P_{\mathrm{out}} = 2 \cdot \pi \cdot n \cdot M$, is determined by measuring the overall rotational speed n and the mechanical torque M of the machine. The electrical input power $P_{in} = 3 \cdot U \cdot I \cdot \cos\varphi$ of the electrical machines is measured using higher accuracy power analysers. It is calculated by the measured voltage U, the current I and the power factor $\lambda = \cos\varphi$. The direct efficiency of an induction motors is expressed as:

$$\eta_{\mathrm{d,Motor}} = \frac{P_{\mathrm{out}}}{P_{\mathrm{in}}} = \frac{2\pi \cdot n \cdot M}{3U \cdot I \cdot \lambda} \tag{13}$$



$$\eta_{\mathbf{d,Motor}} = \frac{P_2}{P_1} = \frac{2\pi \cdot M \cdot n}{\sqrt{3} \cdot U \cdot I \cdot cos\varphi}$$

a) Direct efficiency measurement of induction motors.



$$\eta_{i,\mathrm{Motor}} = \frac{P_1 - P_{\mathrm{fe}} - P_{\mathrm{fw}} - P_{\mathrm{s}} - P_{\mathrm{r}} - P_{\mathrm{LL}}}{P_1}$$

b) Indirect efficiency measurement of an induction motor with reference chapters from IEC 60034-2-1 [27].

Figure 22: Diagram describing the efficiency determination for induction motors.

DOI: 10.5281/zenodo.4733780

7.1.2 Indirect efficiency determination for induction motors

With the indirect method of determining the efficiency, all machine losses that occur (stator winding losses P_S, iron losses P_{Fe}, friction losses P_{fw}, rotor losses P_R and residual losses P_{LL}) are subtracted from the electrical input power of the motor P_1, thus determining the mechanical output power P_2 as depicted in Figure 23. The quotient of both variables then gives the efficiency of the motor. The torque measured for all load points ($1.25 \cdot M_N$, $1.15 \cdot M_N$, $1 \cdot M_N$, $0.75 \cdot M_N$, $0.5 \cdot M_N$, and $0.25 \cdot M_N$) is only used to calculate the residual losses in accordance with IEC 60034-2 -1. Constant offset errors in the torque measurement are eliminated and the influence of the torque on the overall MU of the calculated variable efficiency is significantly reduced. This effect increases with the rated motor power due to the increasing rated efficiency. For this reason, the indirect method for determining the efficiency of ASMs is recommended in the IEC 60034-2-1 standard for all induction motors excluding single phase motors.

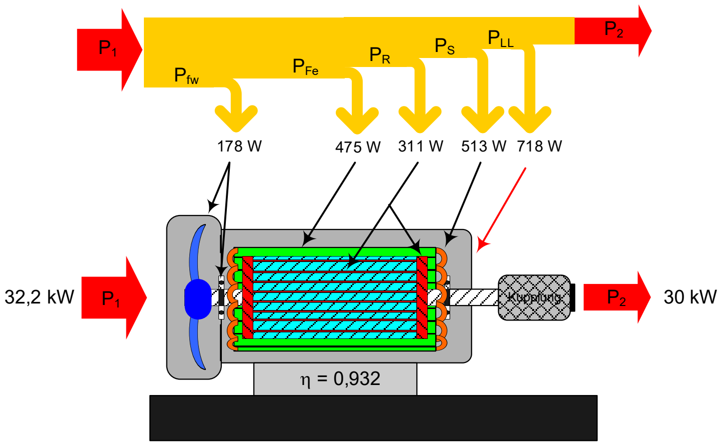


Figure 23: Losses occurring in an induction motor, numerical values as an example [34].

7.2 Efficiency determination for high efficiency class electrical machines (i.e. efficiency classes > IE4 class)

An important criterion in the characterisation of electrical drives in general – and of PMSMs – is the efficiency of the drive which relates to the mechanical power output and the electrical power consumed.

From the metrological point of view, the determination of the efficiency is a challenge, because here two variables are put in relation, the difference of which – the power loss of the drive – is often a power of ten smaller than the variables themselves. In practice, however, this also means that the MUs in the electrical power measurement P_1 and the mechanical power measurement P_2 have a major influence on the result: the power loss and the efficiency. If the machine under consideration falls under an energy efficiency directive of the EU, such as the ASMs under Commission Regulation (EC) No 640/2009, the determined efficiency can possibly decide whether an electrical machine can be placed on the EU market or not – with the corresponding economic consequences for the manufacturer of the machine.

In the case of PMSMs, there are so far no requirements for the minimum efficiency, but here the efficiency is an important instrument for classifying an electrical machine in a comparison of different manufacturers, too. And thus, in addition to the technical data and the price, also an important parameter for the buyer of the machine when comparing several manufacturers.

The efficiency measurement on ASMs and electrically excited synchronous machines is specified in the standard EN 60034-2-1 [27]. And as already written, indirect efficiency measurement is recommended there for ASMs.

An important question in addition to the result, i.e., the efficiency as a numerical value, is the MU with which the efficiency parameter can be specified and its optimisation. And this is where the principal weaknesses of direct efficiency measurement become apparent, both in a PMSM and in an ASM. Since the power loss of the machine is definitely more than a factor of 10 smaller than the power consumed and the output, even small MUs in the electrical and mechanical power measurement lead to significant deviations in the measured variable efficiency.

For a PMSM, no alternative method, such as the indirect method for an ASM, has been specified in the standard in addition to the direct efficiency measurement method. For electrically excited synchronous machines, however, an alternative method to the direct efficiency measurement exists. Due to the physical conditions, this method cannot be transferred to PMSMs. For example, with PMSMs, it is not possible to determine the friction losses without complex intervention in the machine, since the rotor magnets, in contrast to the excitation winding of an electrically excited machine, cannot be switched off and thus a rotation of the rotor inevitably causes iron losses in the stator core.

To use the indirect efficiency determination, the following sources of loss must be separated:

- Stator winding losses P_S
- Iron losses (magnetic reversal and eddy current) P_{Fe}
- Mechanical frictional losses (friction and fan) P_{fw}
- Residual losses P_{LL}
- Harmonic losses P_{vOS}

In order to be able to determine the individual losses, e.g., the friction losses, a non-magnetised rotor is required, which is externally driven. With a PMSM, this reduction in the MU is paid for by an immensely high measurement effort (changing the machine rotor, provision of an additional, non-magnetised rotor), so that this method is not attractive for routine efficiency measurements in the test field.

Few researchers [35] and [36] have only focused on indirect losses and efficiency determination of PMSMs but failed to address MUs for the efficiency determination of those. Low uncertainty test methods are required for determining the efficiency of PMSMs with direct or indirect methods. Most of the work has only focused on induction motor standards for efficiency measurements with the view of the MU [37], [38], and [39]. The uncertainties of the input-output and loss segregation measurements methods in PMSM and SynRMs are investigated in [40], [41], and [42] respectively. A few publications [36] are available with focus on the determination of different losses present in inverter fed PMSMs or SynRMs. All the losses as presented in the papers [36], [40], and [42] as summarised in Table 8 are determined for varying speed and load torque. These losses are used for determining the indirect efficiency of a PMSM. However, measurement methods of losses and indirect efficiency methods suggested in the published paper [36] still consist of uncertainty in the measurement which need further attention.

Table 8: Losses measurements in PMSM [20].

No-load test		Load test	
Generator open circuit test	**Inverter fed no-load test**	**Removed rotor test**	**Inverter fed load test**
Test with non-magnetised rotor • Mechanical losses: friction and windage loss (P_{frw}) Test with PM rotor • No-load iron and mechanical losses (P_{fe0frw})	No-load additional losses (P_{ein0ad}) • Using a modern power analyser • Using a normal power analyser	Current dependent losses & additional stator losses ($P_{\mathrm{cus}} + P_{\mathrm{sad}}$) • Rotor of PMSM is removed and losses are measured including stray field effect	Input power and iron loss ($P_{\mathrm{e1}} + P_{\mathrm{Fe}}$) • The PMSM is measured with the inverter

7.3 Influencing variables and boundary conditions for efficiency determination

This section mentions mainly the evaluation criterion of the MU. The MU depends on the expanded relative uncertainty directly adapted from the calibration certificate of the used measurement instruments and sensors. However, according to national and international standards and the currently used practice

DOI: 10.5281/zenodo.4733780

for measurement instruments and sensors user manuals, the accuracy values are in general stated in the handbook and they are used for uncertainty calculations. Various influencing factors and boundary conditions for uncertainty calculations are present in measurement instruments and measurement sensors used in test benches for electrical machines which increase the uncertainty of the efficiency measurement system of electrical machines. The section summarises and includes all the relevant information on these factors.

The simple direct efficiency determination is used because of its extensive range of applications and according to IEC 60034-2-1. In case of induction motors, it is only recommended for single phase machines. In the case of three-phase machines with higher output power, the MUs regarding the mechanical power measurement based on torque and rotational speed transducers are relatively large. Therefore, it is recommended to use the more complex indirect method for machines for three phase induction motors. [27] In the previous edition of IEC 60034-2-1, the indirect method should be used for induction motors with a rated output power larger than 1 kW. Due to its high MU, challenges related to determine all the related variables that influence the efficiency measurement are currently faced by test bench operators. Therefore, the focus of this section is on efficiency determination for larger machines considering all the measurement instruments used for measuring the electrical and mechanical parameters in a test bench.

The boundary conditions influencing the measured variable efficiency and its MU can roughly be divided into four areas:
(i) measuring devices used and transducers including their MUs fall into the first area. This also includes the fundamental suitability of the measuring device or the transducer for the measuring task, but also the parameterisation of the measuring device. For example, inductive voltage transformers or current transformers, which are only specified and calibrated for a mains frequency of 50 Hz or 60 Hz, cannot be used in connection with converter-fed drives. The power component of the harmonics would not be recorded correctly and the fact that the fundamental component is also influenced, e.g. by saturation effects, is not entirely excluded. In addition, the setting of the power analyser used requires careful consideration. For example, by mistakenly set filters, the harmonic components of the electrical power can be masked out, whereby the determined efficiency would be higher than the true value. It is also important to set the correct measuring ranges and to select transducers adapted to the value range of the measured variable. For example, a torque measuring shaft with a measuring range of up to 1 000 Nm cannot be used with a motor with a rated torque of 30 Nm; the resulting MU would no longer be justifiable. As a guideline, the measured variable should not be less than 10 % of the measuring range.
Another important point (ii) is the time synchronisation of the recording of the measured variables. If all measured variables (electrical and mechanical) are recorded by a power analyser, this requirement is usually not a problem, as the device saves the measured values of all measurement channels at the same time after the measurement process has been triggered. However, if several independent measurement devices must be used due to the number of measurement channels or the spatial extent of the test set-up, the devices must be synchronised with respect to the recording of measured values. If, for example, the electrical power at the converter-input and -output, and the mechanical power of the motor are measured in a converter-fed drive, power fluctuations would not be recorded correctly without time synchronisation.
Another point (iii) is the selection of the measurement method. As already described in section 7.1.2, the indirect method for determining the efficiency of ASMs has clear advantages over the direct method, since the offset errors that are always present in the torque measurement are eliminated by the method and no longer have any influence on the MU. The following exemplary probability density functions (Figure 24) show qualitatively the influence of the measurement method on the MU of the measured variable efficiency. Here, *n* means the rotational speed was measured by an encoder, *s* means the rotational speed was calculated from the mains frequency and the motor slip measured with a slip coil.

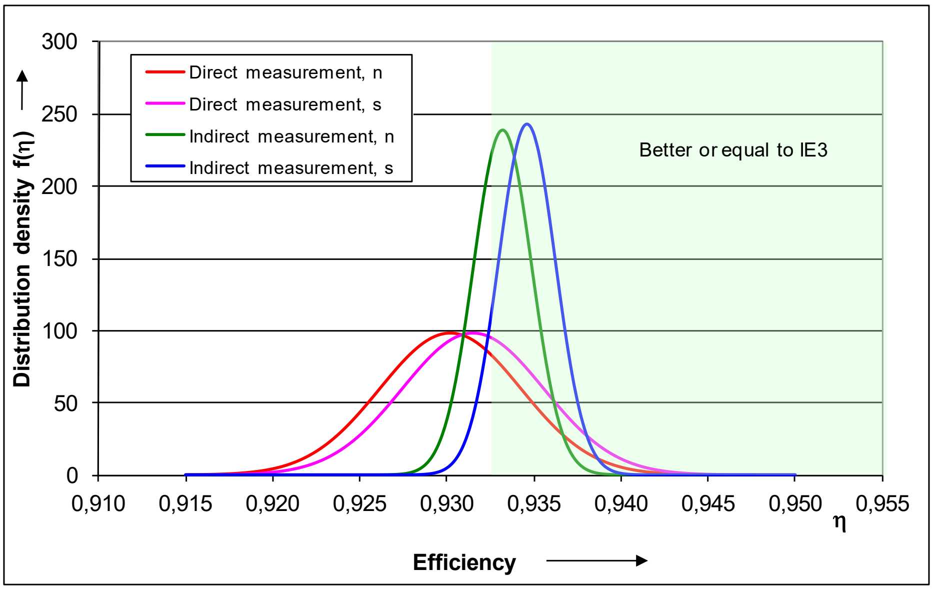


Figure 24: Representation of the result of efficiency determinations in the form of the distribution density function [43].

Table 9 compares the MUs of an exemplary efficiency determination on the same machine using the direct and the indirect method. It is easy to see that the speed measurement method has only a minor influence on the MU of the efficiency, but the difference between the direct and indirect efficiency determination can clearly be seen. The reason for this is the high MU contribution of the torque measurement using the direct measurement method (cf. Table 10).

Table 9: Comparison of different procedures for efficiency determination, example for the machine with a rated power of 30 kW [34].

Procedure	**Direct** ***n*** **measured**	**Direct** ***s*** **measured**	**Indirect** ***n*** **measured**	**Indirect** ***s*** **measured**
P_1	32 048 W	32 048 W	32 048 W	32 048 W
P_2	29 811 W	29 853 W	29 909 W	29 951 W
P_{Vtotal}	2 237 W	2 195 W	2 139 W	2 097 W
η	0.93	0.932	0.933	0.935
Expanded MU (*k* = 2), acc. to **GUM**	$8.1x10^{-3}$	$8.1x10^{-3}$	$3.3x10^{-3}$	$3.3x10^{-3}$
IE class	IE2	IE2	IE3	IE3

And finally, the performance of the measurement and the properties of the test bench used (iv), including the test voltage supply, can have a major influence on the MU. Before starting the measurement of the load characteristic, the thermal steady state for operation with the rated load should have been reached (rate of temperature changed below 2 K/h). Due to the influence of temperature on the electrical resistance, e.g. of the stator winding and also of the rotor in ASMs, the efficiency also changes with the temperature of the motor or generator. Harmonics in the supply voltage of the DUT, e.g. when using a static converter without sufficient filtering instead of a rotating converter, also lead to an increase in the motor power loss. Another problem can arise with the indirect method according to IEC 60034-2-1 if torque fluctuations occur in the individual charging points. This can be caused by controller oscillations and is expressed in an insufficient correlation coefficient (< 0.95) (section 6.1.3.2.6 of IEC 60034-2-1: 2014) during the evaluation. In this case, the determination of the efficiency cannot be used and must be repeated.

DOI: 10.5281/zenodo.4733780

Table 10: MU budget for the efficiency in the case of direct measurement [43].

Quantity	Value	Standard uncertainty	Degree of freedom	Sensitivity coefficient	Uncertainty contribution	Contribution to the overall uncertainty
M	96.00 Nm	0.409 Nm				
Mm	96.00 Nm	0.289 Nm	Infinite	$9.7\cdot10^{-3}$	$2.8\cdot10^{-3}$	47.5 %
Ma	0.0 Nm	0.0289 Nm	Infinite	$9.7\cdot10^{-3}$	$280\cdot10^{-6}$	0.5 %
Mk	0.0 Nm	0.289 Nm	Infinite	$9.7\cdot10^{-3}$	$2.8\cdot10^{-3}$	47.5 %
n	2965.4 min^{-1}	1.15 min^{-1}				
nm	2965.4 min^{-1}	1.14 min^{-1}	Infinite	$310\cdot10^{-6}$	$360\cdot10^{-6}$	0.8 %
na	0.0 min^{-1}	0.0289 min^{-1}	Infinite	$310\cdot10^{-6}$	$9.1\cdot10^{-6}$	0.0 %
P_1	32048.0 W	27.0 W				
Pm	32048.0 W	27.0 W	infinite	$-29\cdot10^{-6}$	$-780\cdot10^{-6}$	3.7 %
Pa	0.0 W	0.289 W	infinite	$-29\cdot10^{-6}$	$-8.4\cdot10^{-6}$	0.0 %
P_2	29811 W	128 W				
π	3.14159265					
eta_{dir}	0.9302	$4.06\cdot10^{-3}$	infinite			

Explanation of the quantities used

M	Torque	P1	**Electric Power**
Mm	Measurement value of the torque	Pm	Measurement value of the el. power
Ma	Resolution error of the torque	Pa	Resolution error of the electric power
Mk	Constant error of the torque measurement	P2	Dissipated mechanical power
n	Speed	eta_{dir}	Motor efficiency
nm	Measurement value of the speed	na	Resolution error of the speed

Result:

	Measurand	eta_{dir}
	Value	0.9302
	Expanded measurement uncertainty	$\pm8.1\cdot10^{-3}$
	Coverage factor	2.0
	Coverage	t-Tabelle 95 %

7.4 Challenges for designing an efficiency determination method for nacelles on NTBs

Based on the knowledge gathered in this report, recommendations for the development of guidelines for calibrating mechanical and electrical power measurement and of a good practice guide for the efficiency determination of devices on test benches are given in the following.

1. For a reliable efficiency determination not only traced mechanical and electrical power measurement is required but also an appropriate synchronisation in a timewise manner.

2. To trace torque measurement in test benches to national standards a suitable transfer standard is required due to the special conditions in test benches regarding parasitic loads. These parasitic loads are caused by misalignments in and along the drivetrain and, in case of system NTBs, an active control system.

3. Due to electro-magnetic fields and other specific environmental conditions that influence the electrical power measurement, it should as well be calibrated in the field using a reference power measurement system.

4. The indirect efficiency determination method which includes the segregation of loss method with linked temperature corrections cannot be applied in test benches on all nacelles. The reason for this is that not all nacelles can be run in idle mode. This therefore leads to a high accuracy of the mechanical power measurement as the direct efficiency determination method needs to be deployed.

5. As wind turbines operate on variable-speed, the efficiency of drive systems and entire nacelles under test should be determined at different load points. This can be achieved by performing so-called efficiency maps or iso efficiency contours.

8 Summary and future work

The investigations on currently existing power curve methods in the field and efficiency determination methods in test benches reveal a lack of non-aerodynamic, standardised, and easily reproducible efficiency determination methods for nacelles based on traceable and applicable measurements. To calibrate mechanical power measurement in test benches using a transfer standard consisting of combined torque and rotational speed measurements, an adequate data transmission for measurements under rotation is required. Different technologies for data transmission were analysed and the most qualified systems are listed in this report. For realising an efficiency determination and to calibrate the mechanical and the electrical power measurement, mechanical and electrical measurement need to be synchronised timely amongst each other and with the measuring devices and the DAQ system in the test bench. Existing synchronisation techniques and their accuracy are introduced. Based on the analysis and the comparison of direct and indirect methods to determine the efficiency of rotating electrical machines, recommendations for the development of a new method for efficiency determination of devices on test benches are given.

Within the project WindEFCY, a standardised efficiency determination method for nacelles and their components on test benches will be developed. Moreover, transfer standards for calibrating both mechanical and electrical power measurement will be developed and set up. The newly developed efficiency determination procedure based on calibrated and synchronised mechanical and electrical power measurement will be implemented in two test benches which are partners in the project WindEFCY: The Dynamic Nacelle Testing Laboratory (DyNaLab) at Fraunhofer IWES in Bremerhaven, Germany, and at the Center for Wind Power Drives (CWD) at RWTH Aachen University, Germany.

DOI: 10.5281/zenodo.4733780

I. Bibliography

[1] E. Hau, Windkraftanlagen, Krailling, Deutschland: Springer-Verlag GmbH Deutschland, 2016.

[2] *IEC 61400-12-1:2017 Wind energy generation systems - Part 12-1: Power performance measurements of electricity producing wind turbines,* 2017.

[3] *MEASNET: Power performance measurement procedure, Version 5,* http://www.measnet.com/wp-content/uploads/2011/06/power5.pdf, 2005.

[4] *IEC 61400-12-1:2005 Wind energy generation systems - Part 12-1: Power performance measurements of electricity producing wind turbines,* 2005.

[5] *IEC 6044-2 Ed 1.2 b: 2003 - Instrument transformers Part 2: Inductive voltage transformers,* 2003.

[6] *IEC 61869-3: 2011 Instrument transformers - Part 3: Additional requirements for inductive voltage transformers,* 2011.

[7] W. Tong, *Wind Power Generation and Wind Turbine Design,* WIT Press, 2010.

[8] G. J. R. S. D. B. L. S. R. M. D. Michael Pagitsch, Feasibility of large-scale calorimetric efficiencymeasurement for wind turbine generatordrivetrains, Munich, Germany: The Science of Making Torque from Wind (TORQUE 2016), October 2016.

[9] H. Zhang und M. Neshati, „An effective method of determining the drivetrain efficiency of wind turbines with high accuracy,“ in *J. Phys.: Conf. Ser. 1037 052013*, 2018.

[10] H. Zhang, J. Wenske, A. Reuter und M. Neshati, „Proposals for a practical calibration method for mechanical torque measurement on the wind turbine drive-train under test on a test bench,“ *Wind Energy,* Bd. vol. 23, Nr. no. 4, pp. 1048-1062, 2020.

[11] *IEEE Standard for a Precision Clock Synchronization Protocol for Networked Measurment and Control Systems,* doi: 10.1109/IEEESTD.2020.9120376, 2020.

[12] *IEEE Guide for Designing a Time Synchronization System for Power Substations,* doi: 10.1109/IEEESTD.2018.8421294, 2018.

[13] A. Mahmood, G. Gaderer, H. Trsek, S. Schwalowsky und N. Kerö, „Towards high accuracy in IEEE 802.11 based clock synchronization using PTP,“ in *2011 IEEE International Symposium on Precision Clock Synchronization for Measurement, Control and Communication*, 2011.

[14] U. Mandal, R. R. Sahani, B. Biswas und H. K. Ratha, „Time Transfer in Wireless Media for Distant Device Synchronization through UHF Link,“ in *2018 International Conference on Recent Innovations in Electrical, Electronics & Communication Engineering (ICRIEECE)*, 2018.

[15] A. Patyuchenko, *60 GHz Wireless Data Interconnect for Slip Ring Applications,* https://www.analog.com/media/en/technical-documentation/tech-articles/60-GHz-Wireless-Data-Interconnect-for-Slip-Ring-Applications.pdf.

[16] *Slip Ring / Frequently Asked Questions,* https://www.moog.com/content/dam/moog/literature/MCG/FAQ_SlipRings.pdf.

[17] „Unleashing the Power of Wi-Fi,“ 2019. [Online]. Available: https://e.huawei.com/de/material/networking/wlan/cbcb731dc6b343c3b0c00194bc14dc62.

[18] G. Dorsey und M. O'Brien, „Fiber Optic Rotary Joints (FORJ) - Performance and Application Highlights,“ 2019. [Online]. Available: https://www.moog.com/content/dam/moog/literature/products/fiber-optic-rotary-joints/MS3324_FORJ-White-Paper.pdf.

[19] „Bluetooth Radio Versions | Bluetooth®-Technology Website,“ [Online]. Available: https://www.bluetooth.com/learn-about-bluetooth/radio-versions/ .

[20] K. Löser, „Wi-Fi 6 in the industry,“ [Online]. Available: https://new.siemens.com/global/en/products/automation/industrial-communication/industrial-wireless-lan.html#Whitepaper.

[21] „Wi-Fi & LoRaWAN Deployment Synergies - Expanding addressable use cases for the Internet of Things,“ https://lora-alliance.org/wp-content/uploads/2020/11/wi-fi-and-lorawanr-deployment-synergies.pdf, 2019.

[22] N. Yogal, *Analysis of a permanent magnet synchronous machine with regard to explosion protection capability,* Dissertation, Technische Universität Braunschweig, 2019.

[23] *IEC 60034-30-1: Rotating electrical machines - Part 30-1: Efficiency classes of line operated AC motors (IE code),* 1st ed., 2014.

[24] J. Fong, F. J. T. E. Ferreira, A. M. Silva und A. T. de Almeida, *IEC 61800-9 system standards as a tool to boost the efficiency of electric motor driven systems worldwide,* Inventions, vol. 5, no. 2, pp. 1-15, 2020.

[25] B. Tsybikov, E. Beyerleyn und P. Tyuteva, „Comparison of energy efficiency determination methods for the induction motors,“ in *MATEC Web Conf., vol. 91*, 2017.

[26] *IEC 60034-1: Rotating electrical machines - Part 1: Rating and performance,* 13th ed., 2017.

[27] *IEC 60034-2-1: Rotating electrical machines - Part 2-1: Standard methods for determining losses and efficiency from tests (excluding machines for traction vehicles),* 1st ed., 2007.

[28] *IEC 60034-2-2: Rotating electrical machines - Part 2-2: Specific methods for determining separate losses of large machines from tests - Supplement to IEC 60034-2-1,* 1st ed., 2010.

[29] *IEC TS 60034-2-3: Rotating electrical machines - Part 2-3: Specific test methods for determining losses and efficiency of converter-fed AC induction motors,* 1st ed., 2013.

[30] *IEEE Standard Test Procedure for Polyphase Induction Motors and Generators,* IEEE Std 112-2004 (Revision of IEEE Std 112-1996).

[31] *C390-10, Test methods, marking requirements, and energy efficiency levels for three-phase induction motors,* 3rd ed., 2020.

[32] A. I. de Almeida, F. J. T. E. Ferreira, J. F. Busch und P. Angers, „Comparative analysis of IEEE 112-B and IEC 34-2 efficiency testing standards using stray load losses in low-voltage three-phase, cage induction motors,“ in *IEEE Transactions on Industry Applications, vol. 38, no. 2*, 2002.

 DOI: 10.5281/zenodo.4733780

[33] C. S. Gajjar, M. A. Khan und P. Barendse, „Analysis of non-intrusive efficiency estimation of induction machines compared to the IEEE 112B and IEC34-2-1 standards," in *2014 IEEE Energy Conversion Congress and Exposition (ECCE)*, 2014.

[34] C. Lehrmann, U. Dreger und F. Lienesch, „Wirkungsgradbestimmung an elektrischen Maschinen: Gegenüberstellung und Optimierung verschiedener Verfahren," *Electrosuisse (SEV Verband für Elektro-, Energie- und Informationstechnik, Verband Schweizerischer Elektrizitätsunternehmen): Bulletin,* pp. 37-43, 2010.

[35] R. Lateb und J. Da Silva, „Indirect testing to determine losses of high speed synchronous permanent magnets motors," in *2014 17th International Conference on Electrical Machines and Systems (ICEMS)*, pp. 1520-1526, 2014.

[36] B. Deusinger, M. Lehr und A. Binder, „Determination of efficiency of permanent magnet synchronous machines from summation losses," in *2014 International Symposium on Power Electronics, Electrical Drives, Automation and Motion*, pp. 619-624, 2014.

[37] L. Aarniovuori, J. Kolehmainen, A. Kosonen, M. Niemelä und J. Pyrhönen, „Uncertainty in motor efficiency measurements," in *2014 International Conference on Electrical Machines (ICEM)*, pp. 323-329, 2014.

[38] G. Bucci, F. Ciancetta, E. Fiorucci und A. Ometto, „Uncertainty issues in direct and indirect efficiency determination for three-phase induction motors. Remarks about IEC 60034-2-1 Standard," in *IEEE Transactions on Instrumentation and Measurement, vol. 65, no. 12*, pp. 2701-2716, 2016.

[39] M. Al-Badri und P. Pillay, „Evaluation of measurement uncertainty in induction machines efficiency estimation," in *2014 IEEE International Conference on Power and Energy (PECon)*, pp. 288-292, 2014.

[40] N. Yogal, C. Lehrmann und M. Henke, „Determination of the Measurement Uncertainty of Direct and Indirect Efficiency Measurement Methods in Permanent Magnet Synchronous Machines," in *2018 XIII International Conference on Electrical Machines (ICEM)*, pp. 1149-1156, 2018.

[41] N. Safin, V. Kazakbaev, V. Prakht und V. Dmitrievskii, „Calculation of the efficiency and power consumption of induction IE2 and synchronous reluctance IE5 electric drives in the pump application based on the passport specification according to the IEC 60034-30-2," in *2018 25th International Workshop on Electric Drives: Optimization in Control of Electric Drives (IWED)*, pp. 1-5, 2018.

[42] Y. Kim, H. Jun, J. Moon, R. Kim, S. Rhyu und S. Jung, „Motor Efficiency Determination of SynRM and Measurement Uncertainty," in *2019 Interational Aegean Conference on Electrical Machines and Power Electronics (ACEMP) & 2019 International Conference on Optimization of Electrical and Electronic Equipment (OPTIM)*, pp. 233-239, 2019.

[43] C. Lehrmann, U. Dreger und F. Lienesch, „Efficiency determination on (explosion-protected) electric machines - a survey under measurement uncertainty aspects," *ant Journal: Electrical Machines,* pp. 30-35, 1 2015.

[44] *IEEE Trial-Use Guide for Testing Permanent Magnet Machines,* 2015.

[45] „FGW," [Online]. Available: https://wind-fgw.de/?lang=en. [Zugriff am 10 03 2021].

II. Acronyms

ASM	asynchronous machine
BER	bit error rate
BS	British Standards
BSS	basic service set
CCI	co-channel interference
COPANT	Pan American Standards Commission
CSA	Canadian Standards Association
DAQ	data acquisition
DOE	Department of Energy
DUT	device under test
EMI	electromagnetic interference
EMPIR	European Metrology Programme for Innovation and Research
EU	European Union
FORJ	fibre optic rotary joint
IEC	International Electrotechnical Commission
IEEE	Institution of Electrical and Electronic Engineers
IoT	internet of things
ISM	industrial, scientific and medical
JEC 37	Japanese Electrotechnical Commission
LE	Bluetooth low energy
MU	measurement uncertainty
NEMA	National Electrical Manufacturers Association
NTB	nacelle test bench
ODFM	orthogonal frequency-division multiplexing
OFDMA	orthogonal frequency-division multiple access
PM	permanent magnet
PMSM	permanent magnet excited synchronous machine
rpm	rotations per minute
SHF	super-high frequency
SynRM	synchronous reluctance motor
TWT	target wake time
UHF	ultra-high frequency
WindEFCY	Wind efficiency
WP	Work Package

DOI: 10.5281/zenodo.4733780

III. Acknowledgements

The project 19ENG08 – WindEFCY has received funding from the EMPIR programme co-financed by the Participating States and from the European Union’s Horizon 2020 research and innovation programme.

The EMPIR initiative is co-funded by the European Union's Horizon 2020 research and innovation programme and the EMPIR Participating States

DOI: [10.5281/zenodo.4733780](https://doi.org/10.5281/zenodo.4733780)