

## Deliverable D5 within 19ENG08

- Report on the technical requirements for the electrical power measurements and definition of the measurands for nacelle test benches -

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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 lists the technical requirements for the electrical power measurements and the definition of the measurands for nacelle test benches.

### 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.

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### Authorship

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## 1 Introduction

The EU must reduce greenhouse gas emission by at least 40 % by 2030 compared to 1990 to tackle climate change and to reach the goal of the Paris Agreement [1]. This can be achieved by an energy transition towards renewable energy sources. Wind energy has much potential and, together with hydro power, the highest share of the total electricity generated from renewable sources. As the renewable energy sector is still competing with fossil energy sources in terms of energy production costs, the efficiency of wind turbine drive trains is to be ameliorated and reliably determined. Moreover, to ensure resilience, security and a high reliability of the power production, extensive testing of wind turbine drive trains and their components on test benches is of great importance. Many tests and validation methods to assure the quality of wind turbines are already standardised [2]. However, all these standardised tests are to be performed in the field. A standard on traceable efficiency determination of wind turbines on test benches based on traceable mechanical and electrical power measurement does not yet exist.

Prior to developing an advanced framework for reliable efficiency determination of wind turbine drive trains on test benches, the electrical power measurement in test benches is to be traced to national standards. To consider all influences in such a special environment, the best way of calibrating the electrical power measurement is on-site via a transfer standard. So far, there is neither such a transfer standard nor a good practice guide about how to perform such a calibration. Before a reference power measurement system (RPMS) can be commissioned, the requirements on typical electrical power measurement systems (EPMSs) used in test benches and, consequently, the requirements on an RPMS must be identified.

This report was generated in Work Package 3 (WP3) of the EMPIR project 19ENG08 “Traceable mechanical and electrical power measurement for efficiency determination of wind turbines” short WindEFCY. Firstly, an insight into energy conversion in wind turbines followed by an overview of the manifold electrical systems in wind turbines and the general set-up of test benches for wind turbines is given. The aim of this report is to create a general overview of energy conversion in wind turbines and, based on this complexity, to identify the requirements on an RPMS. Secondly, the technical specifications of test benches are gathered from stakeholders, such as test bench operators, via a survey. To plan the installation of the RPMS on-site, practical aspects such as available space, expected signal shapes, bandwidth as defined by switching frequency of the frequency converter, accessibility of the individual parts, and environmental conditions are listed in the following. Based on that, the measurands, such as active power as well as the required uncertainty limits of these measurands, are defined.



## 2 State of the art

Wind turbines harness kinetic wind energy to generate mechanical power and, hence, clean and renewable electrical energy. Today, commonly used wind turbines have three-bladed horizontal rotors installed upwind. To optimise power generation under variable speed, modern wind turbines are stall- or pitch-regulated. A wind turbine consists of three main parts: the rotor, the tower, and the nacelle. The nacelle connects the rotor to the tower and is housing the drive train, the main bearing, depending on the wind turbine type the gearbox, the generator, the converter, the transformer, and the entire control and supervisory system. This section is giving an insight into energy conversion in wind turbines, the complexity of electrical systems in wind turbines, and consequently the complexity of nacelle test benches.

### 2.1 Energy conversion in wind turbines

In a wind turbine (Figure 1), the rotor converts a maximum proportion of the fluctuating wind energy into uniform torsion that propels the drive train and, eventually, the generator to produce electrical energy. [3]

There are two main types of wind turbines on the market: direct-drive wind turbines and wind turbines with gearboxes. In direct-drive wind turbines the rotor of the synchronous generator is directly powered by the wind turbine rotor, while in medium- or fast-speed wind turbines the rotor speed on the low-speed shaft (LSS) from typically up to 25 rpm is increased by a gearbox to up to 1600 rpm on the high-speed shaft (HSS). The high-speed values are more favourable to drive an induction generator. The HSS is directly coupled with the generator's rotor. To generate the required electricity and maintain its uniformity, an exciter controlled by the turbine controller based on the predominant wind speed is needed. The current of the generator power is variable, as are voltage and frequency. Because of the very noisy quality of the generator power, it is fed into a power converter. The power converter first rectifies the generator voltage to DC and, afterwards, it converts this DC into a stabilised AC output (trafo power) by a line converter. The sinusoidal trafo power has a frequency of either 50 Hz or 60 Hz depending on the country where the electricity is generated and is directly fed into the transmission grid via a transformer. [4]

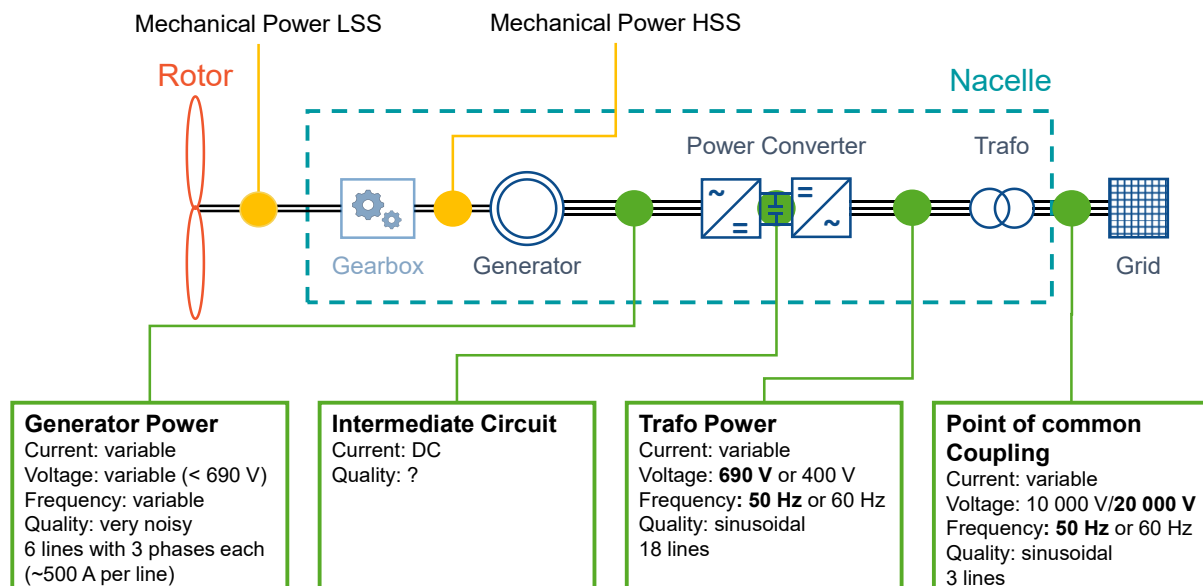


Figure 1: Schematic overview of a wind turbine. Based on [5].

### 2.2 Overview of electrical systems in wind turbines

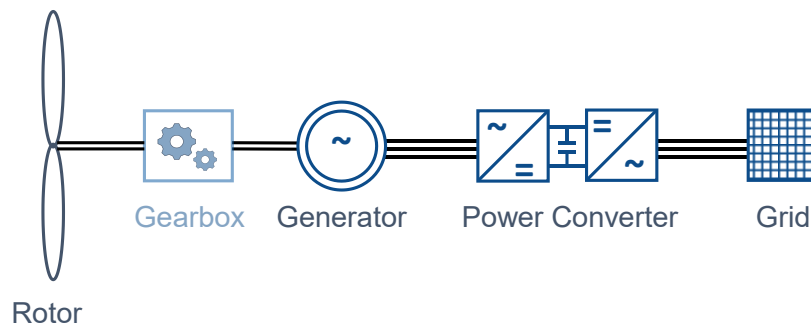
Wind turbines are demanded to produce grid-compatible electric current. This criterion can be met by several combinations of generators and transformers. If the generator is used with power electronic converters, the wind turbine will be able to operate at variable-speed yielding an increased energy



capture. In variable-speed mode, wind turbines operate on variable wind speeds starting at a certain cut-in speed, where the generator produces enough energy to power the wind turbine's controller, up to a cut-out speed, where the entire system is shut down to protect itself from damage due to too high wind loads. However, operation in variable-speed mode makes the generation of AC power at a constant frequency difficult. A constant frequency of power generated in variable-speed operation can be achieved either mechanically or electrically. Several generator types are feasible of power generation by operating on variable-speed: synchronous generators, induction generators (squirrel cage), and wound rotor induction generators (WRIGs). As DC producing generators are expensive, heavy, and feature several other disadvantages, current wind turbines are equipped with three-phase AC generators. Different combinations of generators and power electronics, such as current distribution, the connection to the grid, and monitoring and control, are listed in the following. [3] and [6]

### 2.2.1 Synchronous generators operating on variable-speed

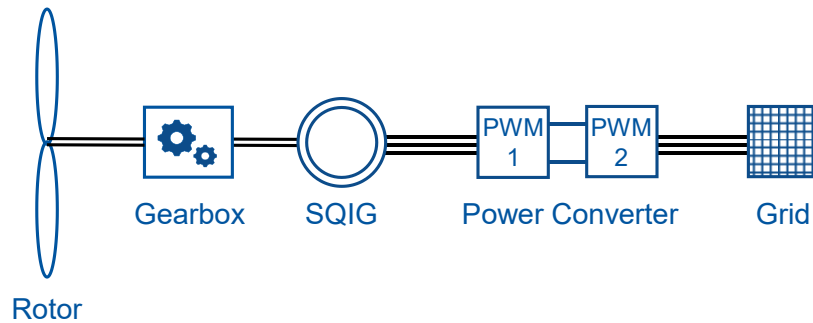
For all synchronous generators, with separately excited fields as well as with fields provided by permanent magnets, the number of poles and the generator speed define the output frequency. When operating on variable-speed, the generator output is fed into a power converter to be rectified to DC and then converted back to good quality AC (Figure 2). In case a multipole synchronous generator is used, the rotor and generator can be connected directly without any gearbox. This is called a direct-drive generator and, consequently, a direct-drive wind turbine. [6] As aforementioned, these direct-drive generators are heavy and large and feature several more drawbacks. In the industry, synchronous generators in connection with a gearbox are used by several wind turbine manufacturers in the onshore and offshore sector. Direct-drive generators are used by Siemens Gamesa Renewable Energy (SGRE), GE Renewable Energy, Shanghai Electrics, Goldwind and other manufacturers.



**Figure 2: Wind turbine with synchronous generator working on variable-speed. Components listed from left to right: rotor, gearbox (not available in direct-drive systems), synchronous generator, rectifier (AC / DC), DC link, inverter (DC / AC), and grid [6]. Own illustration according to [6] p. 247.**

### 2.2.2 Squirrel cage induction generators operating on variable-speed

To deploy a squirrel cage induction generator (SQIG) in wind turbines, a reactive power source is needed. This can be provided by a power electronic converter. Reducing the fatigue damage to most parts of a wind turbine by operating it on variable-speed is the only benefit of this concept as the required power converters are costly and bring along losses that compensate the extra electricity gain of variable-speed operation. In Figure 3, the pulse-width modulation power converter on the left (PWM1) supplies the reactive power for the generator and controls the generator speed. It also accepts the real power from the generator and converts it to DC. This DC power is again converted by the grid side PWM power converter (PWM 2) to suitable AC power.



**Figure 3: Wind turbine with SQIG working on variable speed. Components listed from left to right: rotor, gearbox, induction generator, two PWM power converters with DC link, and grid. Own illustration according to [6] p. 248.**

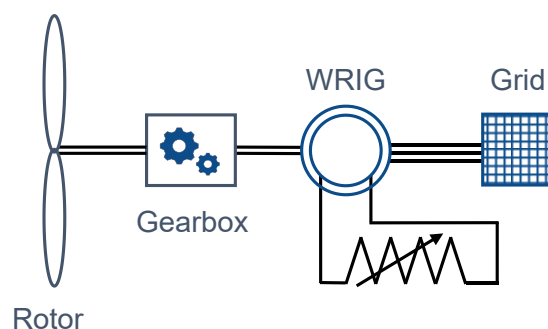
### 2.2.3 Wound rotor induction generators operating on variable-speed

WRIGs are like SQIGs, they can also be operated on variable-speed whereas the required power converters are smaller in capacity which makes them smaller in dimension and less cost-intensive. One main difference between WRIGs and SQIGs is the rotor which has copper wire windings in WRIGs instead of metal bars as in SQIGs.

WRIGs can be operated in high slip operation (Figure 4), slip power recovery (Figure 5), and true variable-speed operation (Figure 6). In the following, the main features, and advantages and disadvantages of all three operation modes are mentioned. More and detailed information can be found in [6], [3], and [7].

#### High slip operation

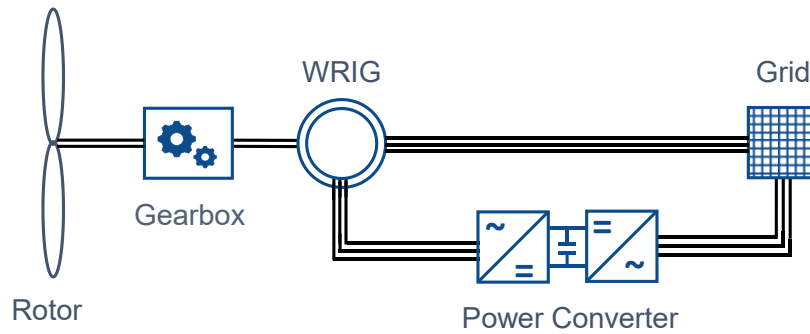
Because of the accessibility of the rotor windings and the rotor circuit in WRIGs, the winding could be short circuited (act like SQIG) and resistance could be changed respectively. In Figure 4, WRIG's outer circle approaches the stator, while the inner circle is connected with the rotor. With the external, variable resistor, the rotor circuit resistance can be increased. As a consequence, the operating speed range increases as well. In case the slip power (rotor power) cannot be recovered, greater losses occur in a high-resistance rotor. The main advantage of this set-up is the ditching of excess power, e.g. evoked by wind gusts, that would otherwise overload the generator.



**Figure 4: Wind turbine with WRIG and external rotor resistance operating on variable-speed. Components from left to right: rotor, gearbox, WRIG, and grid. Own illustration according to [6] p. 249.**

#### Slip power recovery

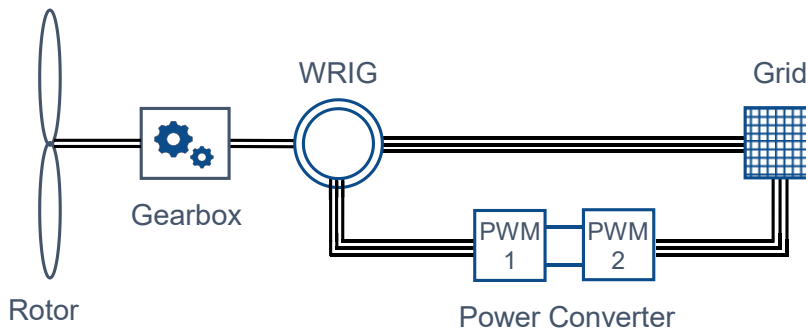
In high-slip operation mode, the rotor power (slip power) is lost. One way on how to recover the slip power is introduced in the following. The frequency of the AC power coming off the rotor, which is the slip frequency times line frequency, can neither be used directly by AC devices nor directly fed into the grid. To rectify this, the slip power can be rectified to DC and, afterwards, inverted to grid frequency AC power by a set-up as shown in Figure 6. Here, the power flows only out of the rotor and its effective resistance is changed. [6]



**Figure 5: Wind turbine with WRIG and slip power recovery working on variable-speed. Components listed from left to right: rotor, gearbox, WRIG, rectifier (AC / DC), DC link, inverter (DC / AC), and grid. Own illustration according to [6] p. 251.**

### True variable-speed operation

Moreover, power can be fed into the rotor to enable sub-synchronous speeds. This operation mode is called true variable-speed and the components are depicted in Figure 6. For this set-up two power PWM converters with a DC link are needed. The rotor-side converter can interact directly with the rotor's AC to feed power into it or convert power coming out of it. In the super-synchronous mode, PWM 1 operates as rectifier and PWM 2 as inverter. In the sub-synchronous mode, it is the other way around. As power is transferred out of the rotor and the stator as well as into both, this entire system is also called doubly fed induction generator (DFIG) and is the most common generator / converter combination in modern wind turbines. DFIGs with PWM converters allow for many control options. [6]

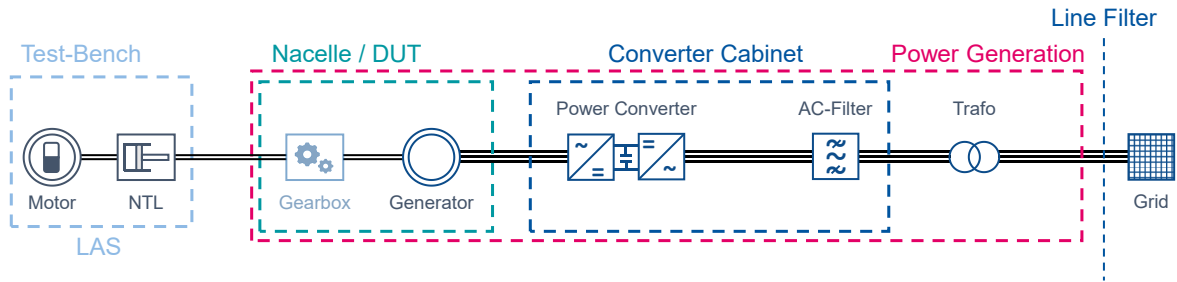


**Figure 6: Wind turbine with doubly fed WRIG working on variable-speed. Components listed from left to right: rotor, gearbox, doubly fed WRIG, two PWM power converters with DC link, and grid. Own illustration according to [6] p. 252.**

## 2.3 Concept of nacelle test benches

As size and type of nacelles and their components vary a lot, so do test benches. In simple end of line (EoL) tests, two nacelles are connected and operated back-to-back. To this end, the driving nacelle is in speed-controlled mode and simple speed loading tests can be performed. For more detailed and realistic tests, so-called nacelle system test benches (NTBs) conducting Hardware-in-the-Loop (HiL) tests are used [8]. These NTBs (Figure 7) comprise a load application system (LAS), the device under test (DUT), and electrical power supply equipment. The LAS replaces the rotor of a wind turbine and consists of a motor and a non-torque loading (NTL). During HiL tests of entire nacelles wind load events, such as gusts and wind shadow evoked by the tower, can be simulated with the help of external forces and bending moments which are generated by the NTL. The electrical power supply equipment can consist of a converter cabinet, a trafo, and an artificial grid. The converter cabinet houses a power converter and an AC-filter. The electrical power supply equipment is used in case the DUT does not bring along an inverter and the components behind it. Like real wind turbines, the inclination angle varies between 4° and 6°. In [9], NTBs around the world with nominal power ranging from 1 MW at DTU Danmarks Tekniske Universitet up to 25 MW at LORC Lindø Offshore Renewables Center are listed [10].





**Figure 7: An NTB consists of a motor and an NTL (left) to drive the DUT and a converter cabinet and a line filter (right) to rectify and transform the electricity for the artificial grid. Based on [5].**

### 3 Electrical requirements for nacelle test benches

The currents and voltages depend on the NTB. Each NTB has different measuring points where different current and voltage levels occur. Below, some details of the NTBs at FhG IWES, RWTH Aachen, and CENER are introduced. Moreover, some information about the medium- and the high-speed generator test bench at CENER can be found.

#### 3.1 FhG IWES

The dynamic nacelle testing laboratory (DyNaLab) located at Fraunhofer IWES (FhG, institute for wind energy systems) is an NTB for complete nacelle testing. DyNaLab (Figure 8) provides a realistic testing environment consisting of mechanical tests and a grid emulator for multi-megawatt nacelles. The artificial network of 44 MVA installed converter power allows for nacelle testing up to 10 MW. Using the HiL method and the NTL, typical grid faults and other expected loadings can be simulated. [11] The number of phases to be measured amounts to three. The maximum voltage level in the NTB is 36 000 V, while the maximum current level is below 700 A.

In the entire NTB, a timewise synchronisation of all measuring devices is realisable via GPS timestamps, precision time protocol (PTP), network time protocol (NTP), and inter range instrumentation group timecode B (IRIG-B).

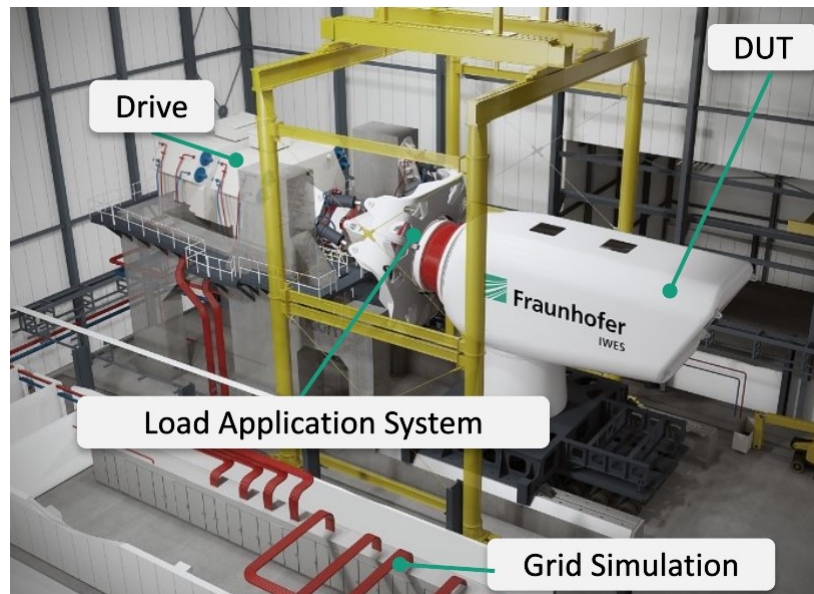


Figure 8: NTB DyNaLab at FhG IWES in Bremerhaven, Germany. Modified based on [12].

##### 3.1.1 Electrical power supply equipment in the NTB

A schematic overview of the DyNaLab is given in Figure 9. Besides the coupled motors (left) to drive the DUT (specimen), the electrical power supply equipment (right) is shown. At the primary side of the transformer (between transformer and junction box, two transformers being connected in parallel), three phases with a maximum voltage level of 20 kV, a maximum current level of less than 126 A, and a bandwidth of up to 20 kHz are to be measured. The harmonic components need to be determined during test measurements at the beginning of the measurement campaign. At the secondary side of the transformer (between specimen and transformer), two times three phases with a maximum voltage level of 630 V and a maximum current level below 4 000 A are to be measured.

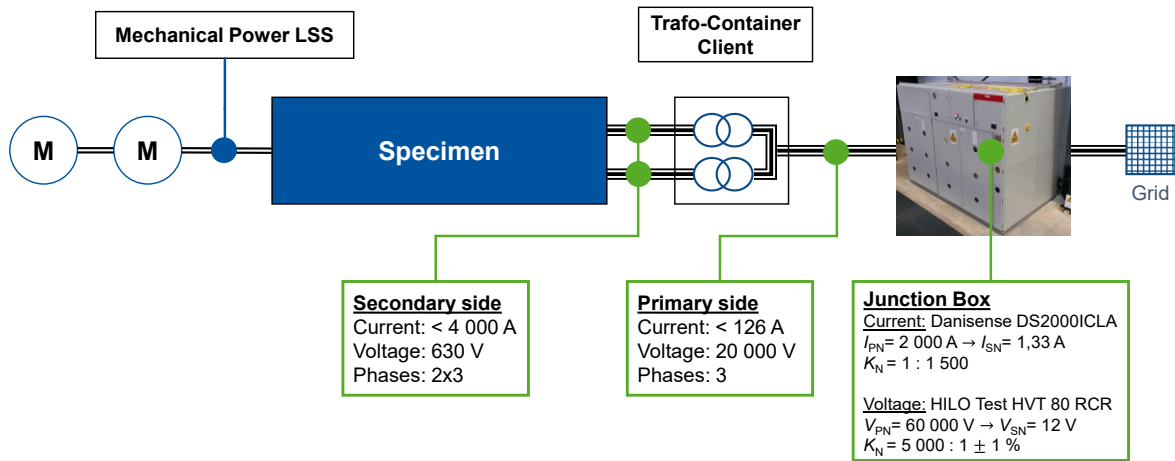


Figure 9: Schematic overview of the DyNaLab, FhG IWES.

The EPMS is installed in the junction box (Figure 10). The current sensors (Danisense DS2000ICLA) are located on the left and the voltage sensors (HILO Test HVT 80 RCR) on the right.

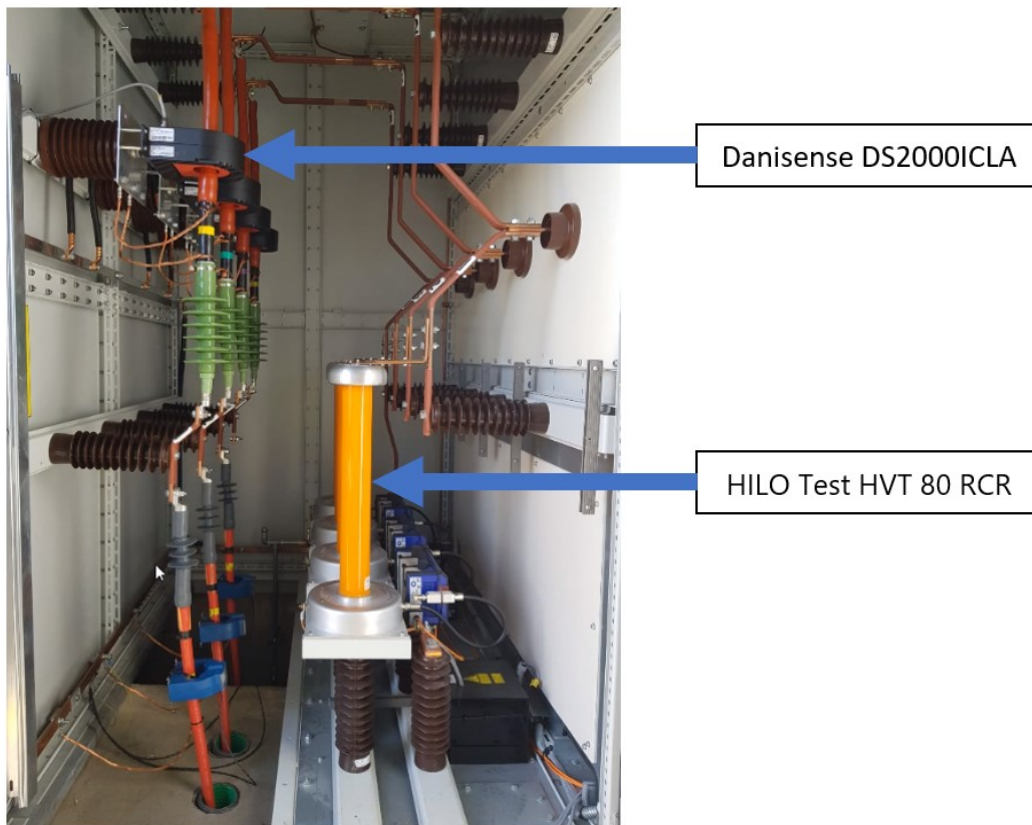


Figure 10: Inside of the junction box, medium voltage (FhG IWES).

- **Current measurement based on the Hall effect** (Danisense DS2000ICLA, Figure 10)
  - $I_{PN}$  Primary nominal current rms 2000 A
  - $I_{SN}$  Secondary nominal current rms 1.33 A
  - $K_N$  Conversion ratio 1 : 1500
  - BW Bandwidth (-3dB, small signal 10 App) 300 kHz

**Table 1: Accuracy specification of the current measurement.**

The accuracy specification is based on: sinusoidal current, ambient temperature $+23\pm 3$ °C, calibration interval of one year, primary conductor in the middle of the transducer		
Frequency	Accuracy specification for amplitude in % of nominal input current rms	Accuracy specification for phase in °
DC ... 2 kHz	$\pm 0.01$ %	$\pm 0.04$ °
2 kHz ... 10 kHz	$\pm 1.5$ %	$\pm 0.5$ °
10 kHz ... 100 kHz	$\pm 3$ %	$\pm 3$ °

- **Voltage measurement** (HILO Test HVT 80 RCR, Figure 10)
  - $V_{PN}$  Primary nominal current rms 60 kV (AC, 50 Hz)
  - $V_{SN}$  Secondary nominal current rms 12 V
  - $K_N$  Conversion ratio 5000 : 1  $\pm 1$  %
  - BW Bandwidth, appr. 10 MHz
- And HBK measuring card GN401 and GN610B

Available space for reference measuring devices for the calibration of installed measuring devices and measuring sensors (EPMS):

- Hall A around the machine carrier on a scaffold
- Secondary side inside the container (LV) Rogowski coils for current measurements
- Junction box medium-voltage (MV) in the right-hand switching field good installation option for U and I sensors; the data acquisition (DAQ) system can be placed in the low-voltage (LV) field

### 3.1.2 Environmental conditions at FhG IWES laboratory

At the DyNaLab of FhG IWES, the ambient conditions within the laboratory are monitored centrally at a wind-protected place in the laboratory, which is a large-sized hall (Figure 8). The laboratory is neither air-conditioned nor humidity controlled, only an exhaust air system is available. In general, the temperature can vary between 15 °C and 35 °C, normally the temperature is between 15 °C and 18 °C, but in summer times it can get as high as 23 °C to 25 °C due to high temperature outside. In winter times, a heating system can raise the temperature inside the hall to about 16 °C. All heat-generating aggregates of the test bench itself and of DUTs are fluid-cooled if not requested differently. Air cooled systems can be integrated individually if needed for a sufficient DUT cooling. The measurement data in Figure 11 shows temperature and humidity data of the DyNaLab gathered on 22/05/2019. At an outside temperature of about 12 °C and a relative humidity of 83 %, the temperature inside was stable to 3 K between 20.6 °C and 23.73 °C and the relative humidity inside was stable to 9 % between 45.06 % rH and 36.06 % rH.

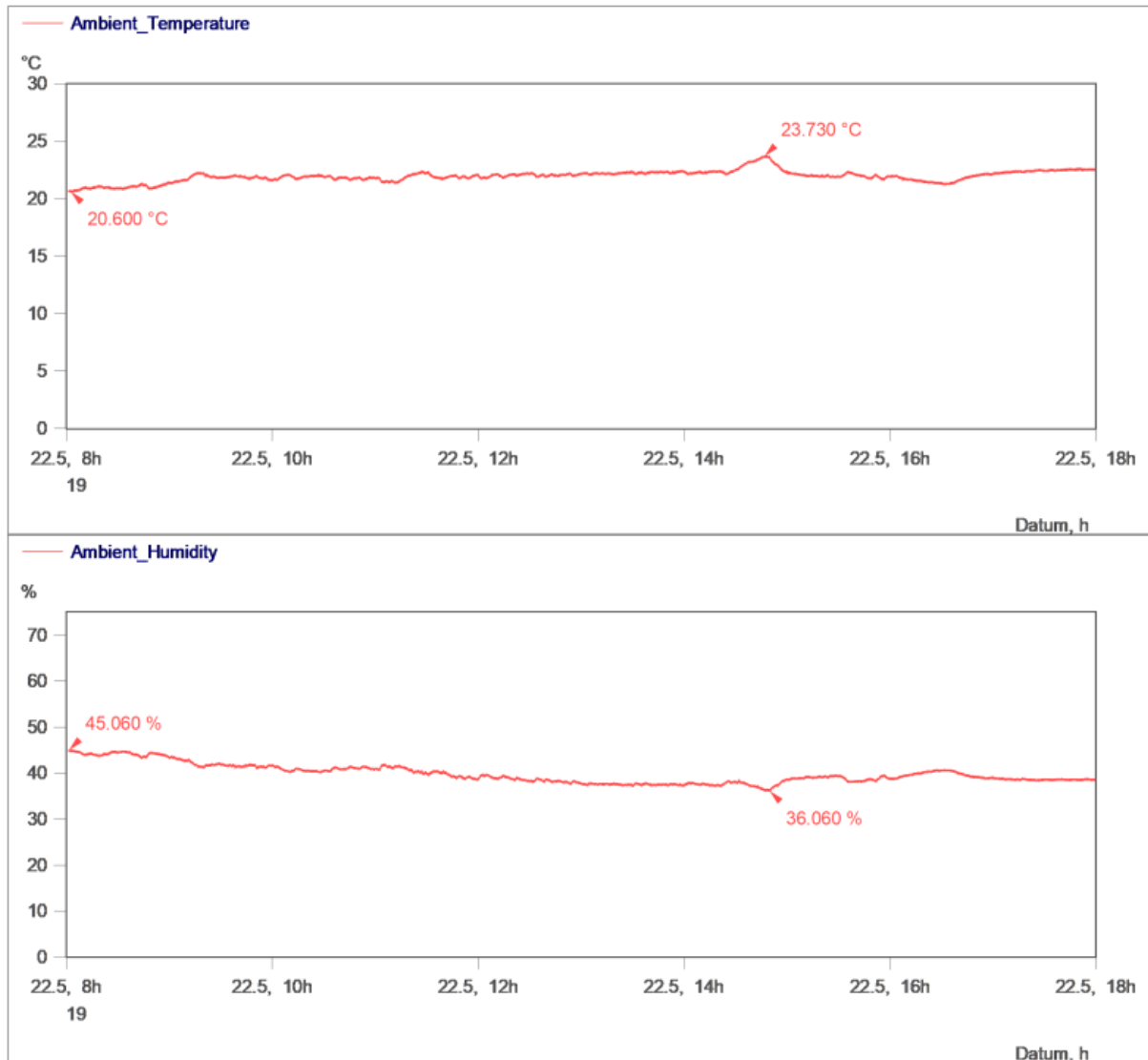


Figure 11: Environmental data temperature and humidity recorded at FhG IWES on the ground of the DyNaLab hall next to the DUT on 22/05/2019. On that day, the outside temperature was 12 °C and the humidity fell from 83 % rH at 1016 hPa down to 68 % rH at 1018 hPa.

### 3.2 RWTH Aachen

The Center for Wind Power Drives (CWD) at RWTH Aachen University owns a 4 MW NTB to examine nacelles of onshore wind turbines and their components, such as gearboxes, main bearings, and entire drive trains. The NTB uses a permanent-magnet motor to drive the DUT directly. As it is a system NTB, HiL grid and wind load tests can be performed whereas wind loads are simulated by an NTL (Figure 12). For research purposes, RWTH has a research nacelle on hand. This nacelle has a rated power of  $P_{nom} = 2.75$  MW and is owned by the Forschungsvereinigung Antriebstechnik e. V (FVA). It is generically neutralised to be able to investigate every detail of the nacelle deeply and to publish all the results. [13] and [14]

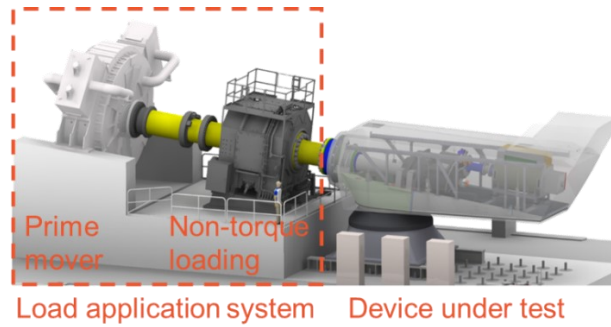


Figure 12: NTB at CWD of RWTH University in Aachen, Germany. Modified based on [15].

### 3.2.1 Electrical power supply equipment in the NTB

The typical measuring points for mechanical and electrical power are shown in Figure 13 and Figure 14. Moreover, Figure 13 and Figure 14 list the prevailing current, voltage, frequency, and quality of the signals between all electrical components in the FVA nacelle.

The DAQ system consists of amplifiers from the HBK QuantumX Modules Series. Used QuantumX Module amplifiers are MX410B, MX840B, MX1601B, and MX1615B.

All measuring devices are synchronised in a timewise manner by PTP.

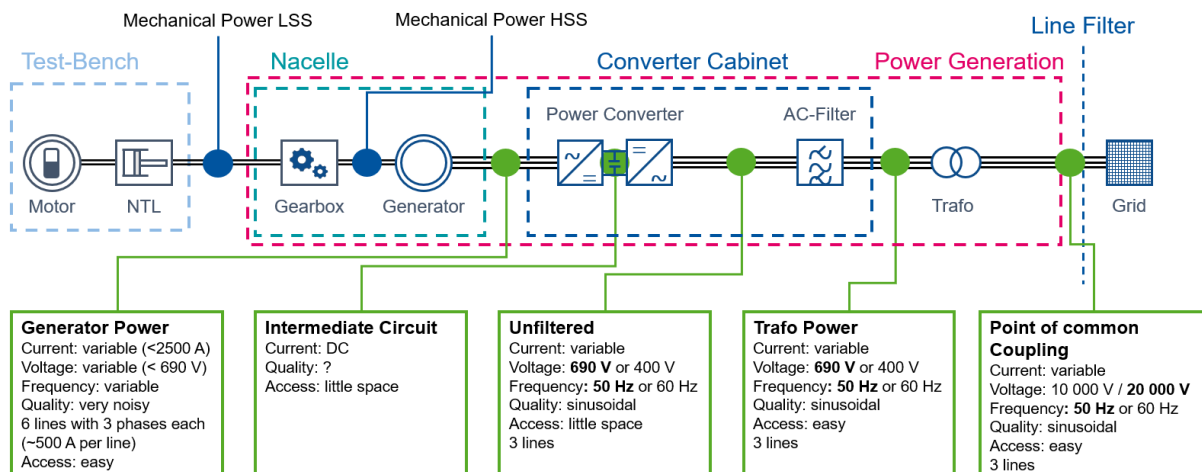


Figure 13: Research set-up at CWD of RWTH Aachen University. 4 MW NTB housing the 2.75 MW research nacelle of FVA.

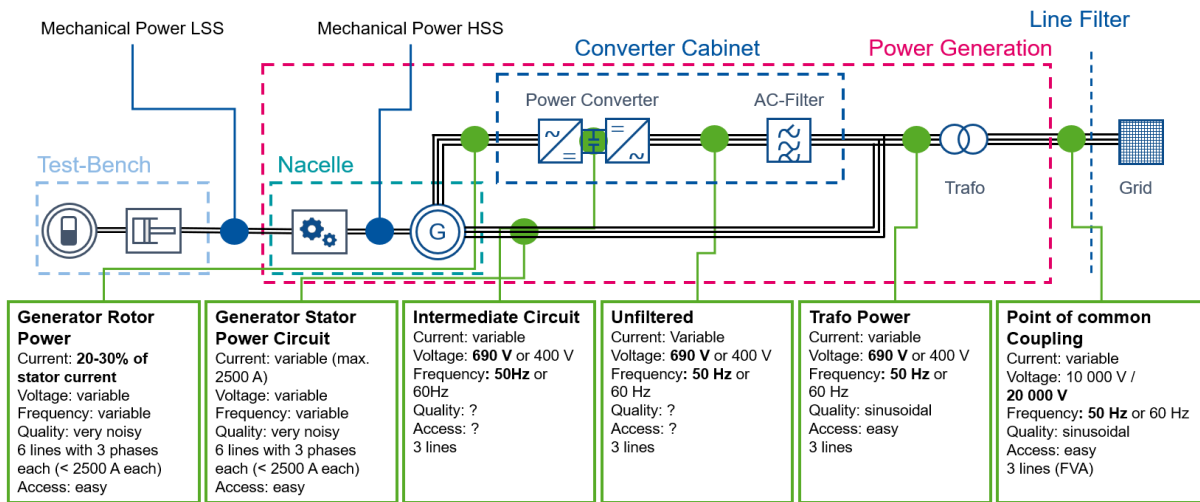
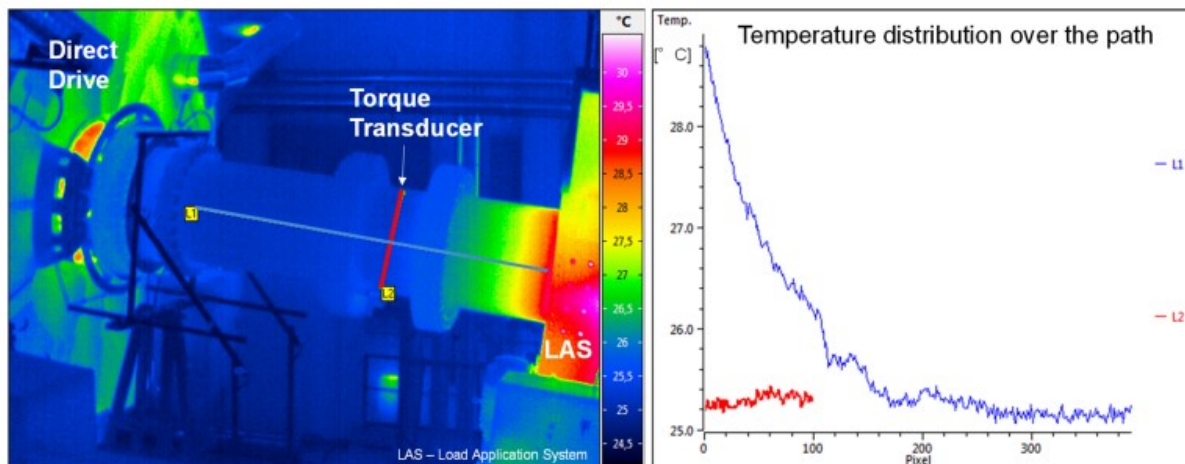


Figure 14: Research set-up at CWD of RWTH Aachen University. 4 MW NTB housing the 2.75 MW research nacelle with a DFIG.

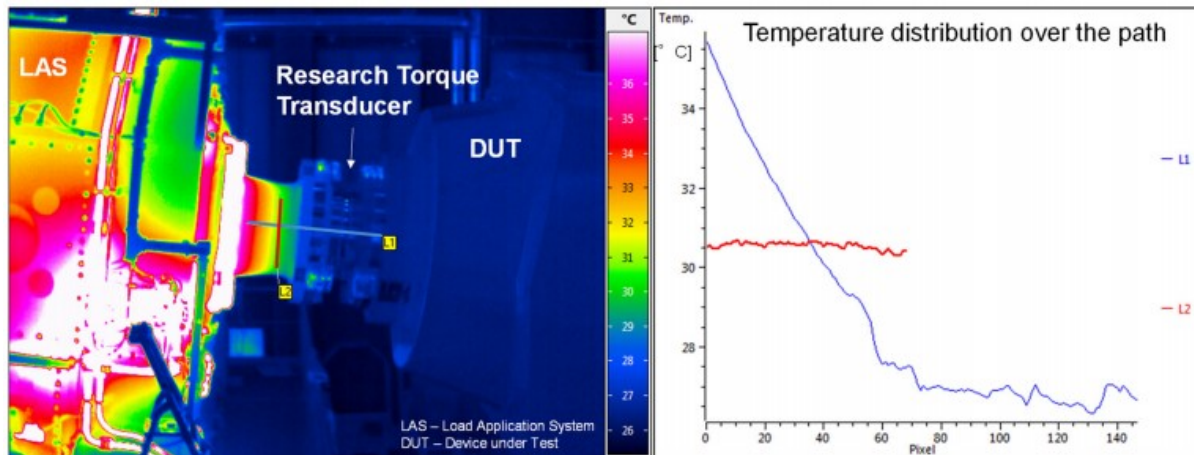
### 3.2.2 Environmental conditions at RWTH Aachen laboratory

For a research project, the temperature distribution along the drive train of RWTH's NTB was measured using a thermographic camera. According to [15], the temperature at the torque transducer, which is mounted between the prime mover and the LAS (NTL) (Figure 15a) increases by 4 K during a full-load operation lasting ten hours. Same applies for the region between the LAS and the DUT (Figure 15b). The surrounding temperature inside the testing hall is typically between 15 °C and 25 °C.

To minimise electromagnetic interference, the converter of the motor is spatially separated from the rest of the NTB in a specially dedicated room. Moreover, all cables are shielded, and signal and power wiring are separated from each other. Cable ducts are additionally shielded. The electronics of the DUT are housed in three electric cabinets.



(a) Temperature distribution between the direct drive (left) and the LAS / NTL (right).



(b) Temperature distribution between the LAS / NTL (left) and the DUT (right).

Figure 15: Temperature distribution along the drive train of RWTH's NTB measured by a thermographic camera [15].

### 3.3 CENER

The National Renewable Energies Centre (CENER) in Spain owns a powertrain test laboratory that includes facilities for electrical testing. The test benches are designed to perform functional, load and accelerated lifespan tests on wind turbines and their components up to 6 MW. Besides a medium-speed and a high-speed generator test bench with equipment for LV and MV measurements, CENER operates a 6 MW NTB (Figure 16 and Figure 17). The NTB uses a motor / gearbox combination to generate the required power to drive the nacelle under test. Moreover, HiL wind loads can be simulated by the available NTL. For a timewise synchronisation of all the equipment in the test laboratory, NTP is used.

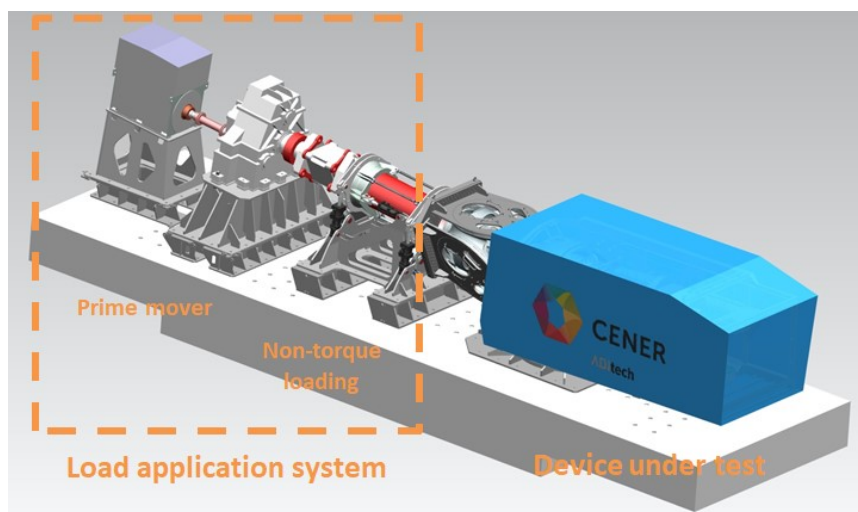


Figure 16: 6 MW NTB of CENER located in Sangüesa, Spain. [16]



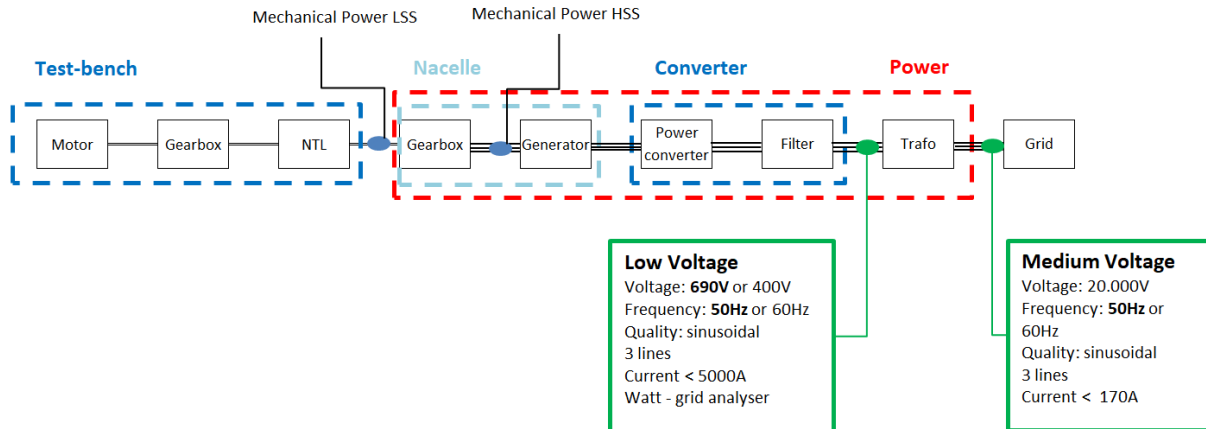


Figure 17: 6 MW NTB of CENER located in Sangüesa, Spain.

### 3.3.1 Medium-speed generator test bench

In the medium-speed generator test bench, motor and generator are directly coupled (Figure 18). The rotational speed in this test bench ranges from 0 rpm up to 773 rpm. The maximum torque that can be generated amounts to 190 kN m.

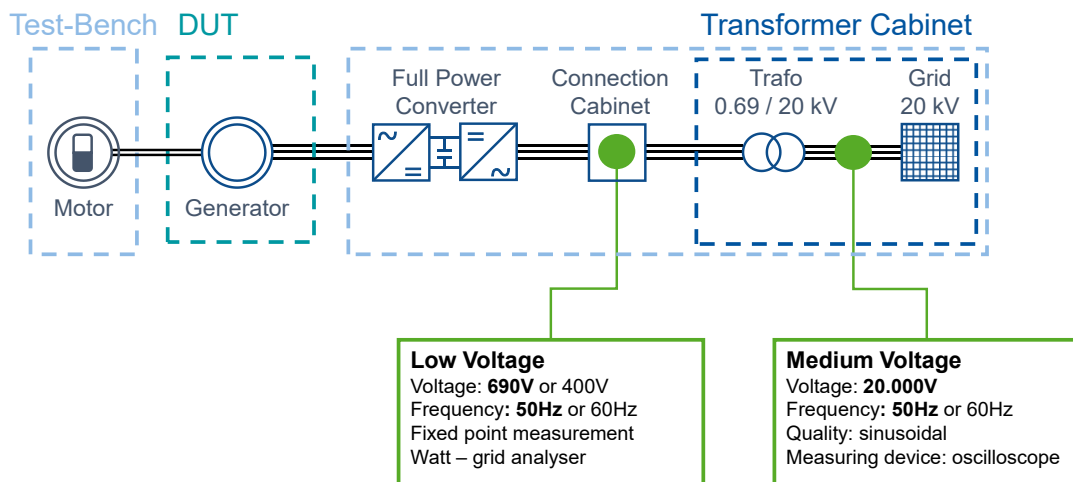
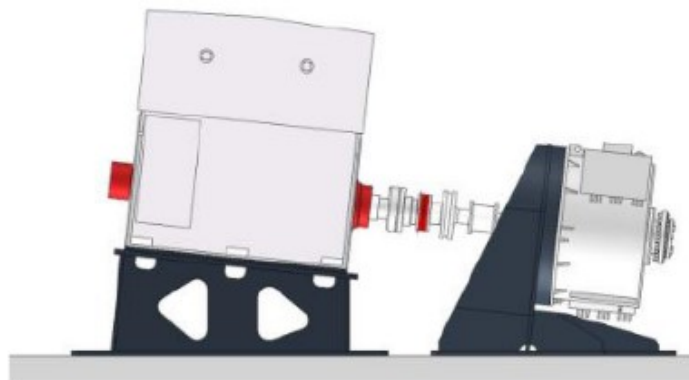


Figure 18: Medium-speed generator test bench at CENER in Sangüesa, Spain. The motor (left) is directly coupled with the generator under test (right).



### 3.3.2 High-speed generator test bench

On the high-speed generator test bench (Figure 19) of CENER, the motor and the DUT are coupled through a gearbox. The rotational speed ranges from 0 rpm to 2320 rpm with a maximum torque of 63 kN m.

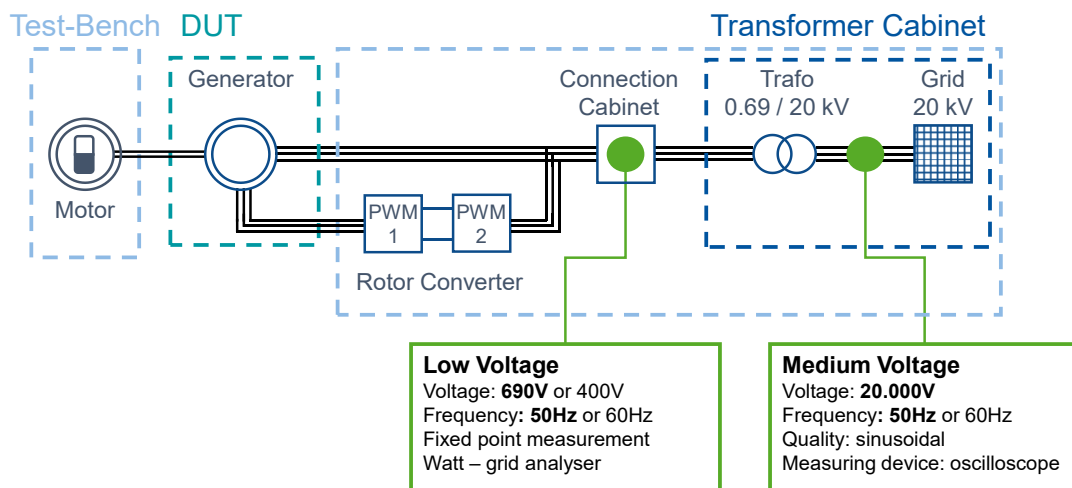
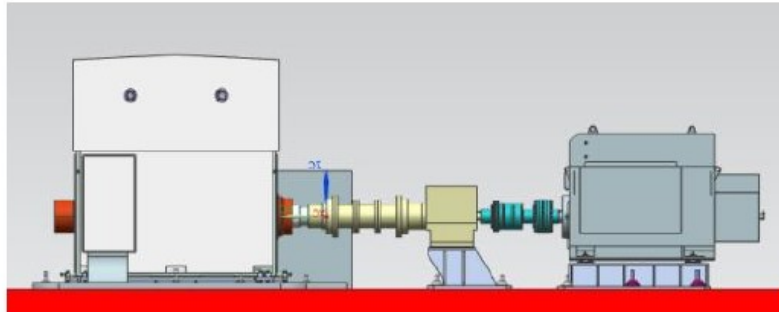


Figure 19: High-speed generator test bench at CENER in Sangüesa, Spain. The motor (left) drives the DUT (right), which is a high-speed generator.

### 3.3.3 Electrical power supply equipment in the test benches

The electrical power supply equipment has available LV and MV measurement devices.

#### Low voltage measurement

LV measurement is only possible at a specific point. It is located in the connection cabinet (Figure 20) and can automatically be switched. With the power analyser deployed, direct voltage measurement and harmonic analysis is feasible.

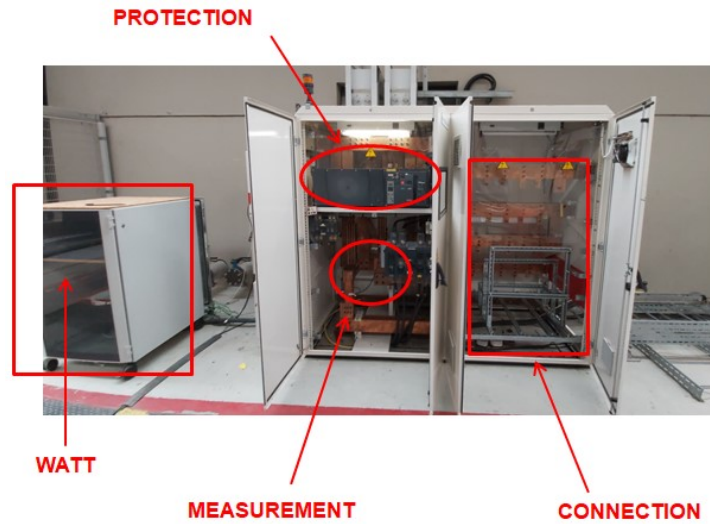


Figure 20: Connection cabinet to measure LV at CENER.

**Medium voltage measurement**

For MV, points of measurement are also available. The measuring equipment is placed in a separate transformer cabinet (Figure 21). MV probes and differential voltage probes are available to be used with an oscilloscope.



Figure 21: Transformer cabinet for MV measurements at CENER.

Table 2: Equipment for electrical measurements.

	MEASUREMENT SYSTEM		VOLTAGE PROBES		CURRENT PROBES	
<b>LOW VOLTAGE</b>	Yokogawa	WT-1600	N/A - Direct measurement		Chauvin Arnoux	P01120509
<b>MEDIUM VOLTAGE</b>	Yokogawa	DL750p	Yokogawa	700224	Chauvin Arnoux	P01120505



### 3.3.4 Environmental conditions at CENER laboratory

Inside CENER laboratory, both temperature and humidity are recorded continuously but are not controlled in any way. The temperature ranges from 5 °C to 35 °C, while the humidity varies between 40 % to 80 % rH. In most cases, it is defined that all components need to be fully warmed up before any non-torque loads are applied. The warming up is done by setting the prime mover to the nominal speed and increasing the torque stepwise afterwards. Each step is operated for about 15-20 min. Consequently, the entire warming up process takes approximately one hour. The thermal equilibrium is defined by means of the temperature of the gearbox's lubricant oil. The temperature is not measured directly along the drive train, but through the cooling system fluids, lubrication system fluids, covers of the generators and the power converters and the air inlets and outlets of the nacelle cooling systems. These temperatures are used to calculate the different losses of nacelle sub-systems, such as the gearbox and the generator.

In order to minimise electromagnetic interference, the power electronic converters and transformers are located in a special separated room. Moreover, different grounding systems for power wiring and control wiring are available.

## 3.4 Technical requirements for electrical power measurements in NTBs

The technical requirements for power measurement in NTBs are based on a previously conducted survey among test bench operators.

The electrical power<sup>1</sup>  $P_e$  is calculated with:

$$P_e = \frac{1}{T_e} \int_0^{T_e} u(t) \cdot i(t) dt \quad (1)$$

While  $u(t)$  and  $i(t)$  are voltage and current respectively, the time interval  $T_e$  should ideally be chosen to be an integer multiple of the signal period and the mechanical rotation period.

The aim is to develop a metrological framework for the measurement of the electrical part of the whole nacelle as well as of individual parts (e.g. generator, frequency converter, auxiliary systems, filter etc.). The measurand is power at 50 Hz, because only power at 50 Hz is desirable in the grid within the EU. However, the relevant signals are rich in harmonics and interharmonics. These are disturbances. The power measurement should be immune to them. It is common practice to measure up to the 50<sup>th</sup> harmonic of 50 Hz (i.e. 2.5 kHz) or the second harmonic of the switching frequency of the frequency converter (e.g. 5 kHz), whichever is higher. The measurement of this parameter is made traceable.

The electromagnetic environment of an NTB is challenging. It affects the behaviour of common measuring systems. Due to the size of an NTB, grounding is not trivial. The design and calibration of the measuring system needs to account for this.

### 3.4.1 Definition of the measurands for NTBs

In order to determine the efficiency in an NTB, the following measurands were defined. The RPMS must be able to record and process these.

- Current
- Voltage
- Total Harmonic Distortion (THD)
- Active power
- Power factor
- Frequency

In addition, the apparent power, reactive power, energy and the spectrum (harmonic content) can be measured.

<sup>1</sup> For simplification, the calculated electrical power is shown assuming a single-phase system.



### 3.4.2 Electrical characteristics of current and voltage sensors

The current and voltage sensors must meet the requirements of the survey above (sections 3.1 to 3.3). The relevant signals (Table 2) are rich in harmonics and interharmonics. Therefore, the reference sensors should have a 3 dB bandwidth of 20 kHz. The actual calibration of the individual sensors is aimed at up to 5 kHz, since the RPMS should have a bandwidth of up to 5 kHz. To calibrate the reference sensors, a suitable generation must be available. Each test bench has different measuring points. Therefore, the requirements for the measurement sensors are different. The calibration of the EPMS in test benches is performed at a fundamental frequency of 50 Hz. To determine the efficiency of a nacelle under test, a mechanical input power and an electrical output power is required. This electrical output power can be measured on the MV side of the MV transformer. The voltage there is less than 20 kV and the current is less than 300 A. Another possible measuring point would be on the LV side of the transformer. At this point the voltage is less than 1 000 V and the current is less than 3 000 A. In some test benches, it is not possible to measure on the secondary side because there is no space for measuring equipment. Some commercial sensors require an external power supply. A 230 V connection must be available in the test benches.

**Table 2: Overview of available signals in NTBs.**

Signal	Sinusoidal distorted multi-level waveforms below 10 kHz
LV side	< 700 V rms (1 000 V peak) < 2 000 A rms (3 000 A peak)
MV side	< 20 000 V phase to phase (12 kV phase to ground) < 300 A rms
Calibration frequency	50 Hz
Bandwidth reference current transformer	20 000 Hz (-3 dB bandwidth)
Bandwidth reference voltage divider	20 000 Hz (-3 dB bandwidth)
Bandwidth RPMS	5 000 Hz
Electrical supply voltage	230 V
Electrical interface	measuring lead (spring-loaded), D-SUB 9 pins

### 3.4.3 Electrical characteristics of the power analyser

The power analyser must meet the requirements of the survey above (sections 3.1 to 3.3) when used with suitable sensors (section 3.4.2). The relevant signals (Table 3) are rich in harmonics and interharmonics. Therefore, the bandwidth of the power analyser should be larger than that of the sensors. The actual calibration of the power analyser is aimed at up to 5 kHz since the RPMS should have a bandwidth of up to 5 kHz. To calibrate the power analyser, a suitable generator must be available. While each test bench has different measuring points requiring different sensors, their secondaries will be very similar. Therefore, the requirements for the power analyser do not depend on the measuring points. The calibration of the EPMS in test benches is performed at a fundamental frequency of 50 Hz. To determine the efficiency of a nacelle under test, a mechanical input power and an electrical output power is required. This electrical output power can be measured behind on the MV side of the MV transformer. The voltage occurring there is larger than 1 000 V, requiring the use of voltage sensors. Another possible measuring point would be on the secondary LV side of the transformer. At this point the voltage is less than 1 000 V and can be measured directly. At both points, the current exceeds the specifications of commercial power analysers; sensors or transformers need to be used. A 230 V connection must be available in the test benches.

**Table 3: Overview of available signals in NTBs.**

Signal		Sinusoidal distorted multi-level waveforms below 10 kHz
Inputs for direct connection	$\leq 1000$	V rms
	$\leq 10$	A rms
Input for sensor connection	$\leq 4$	V rms (proportional to primary voltage)
	$\leq 4$	V rms (proportional to primary current)
Calibration frequency	50	Hz
Bandwidth power analyser	100	kHz
Electrical supply voltage	230	V
Electrical interface		Ethernet
Additional inputs	mandatory	for synchronisation
	optional	for mechanical measurements (e.g. torque or speed)

### 3.4.4 Torque and rotational speed sensor signal

**Table 4: Measurement technology to gather torque and rotational speed signals.**

Torque sensor	Strain gauges on surface of the test specimen
Rotational speed sensor	Absolute encoder
	Incremental encoder

More details about measuring and calibrating rotational speed will be explained in *Deliverable D2 within 19ENG08: Report describing the requirements of tachometers such as the evaluation of existing tachometer measuring principles and their capabilities, and the procedure developed to calibrate tachometers with an uncertainty of 0.01 %*. More information about measuring torque in the MN m range traceably will be provided in *Deliverable D3 within 19ENG08: Report describing the calibration of the 5 MN m torque transfer standard partially up to 1.1 MN m with an uncertainty < 0.1 % and in the full range up to 5 MN m with an uncertainty < 0.5 % with synchronised measurements of rotational speed up to 20 min<sup>-1</sup> on the low-speed shaft respectively torque measurements up to 100 kN m with synchronised measurements of rotational speed up to 1600 min<sup>-1</sup> on the high-speed shaft*.

### 3.4.5 Environmental conditions

**Table 5: Ambient conditions in NTBs.**

Temperature in the hall	15 - 25	°C
Relative humidity in the hall	40 - 60	%

The next step is to define and set up the RPMS for all relevant electrical parts of the nacelle. This system is composed of a suitable multi-channel power analyser and wideband current and voltage sensors that meet the aforementioned requirements.



## 4 Conclusion and future work

To trace the electrical power measurement in NTBs to national standards under consideration of various influences via a transfer standard, the requirements for a RPMS are defined within this report. The overview of manifold electrical systems in wind turbines and both the general and the specific set-up of NTBs gives an insight into the complexity of the requirements for an RPMS and the definition of the measurands in an NTB. Not only practical aspects such as available space, but also expected signals shapes and maximum current and voltage are gathered and defined for the further course of the project WindEFCY.

Within the WindEFCY project, the electrical power supply equipment of two different NTBs will be calibrated using the RPMS developed based on the requirements defined in this report: at (1) DyNaLab of FhG IWES in Bremerhaven and at (2) CWD of RWTH in Aachen, both in Germany. As an overall aim, an advanced metrological framework for the measurement of the electrical part of the whole nacelle as well as of individual parts including a *Good Practice Guide on the calibration procedure for traceable electrical power measurement at the generator, converter and the filter using a reference power measurement system* will be developed.



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## II Acronyms

AC	alternating current
CENER	National Renewable Energies Centre
CWD	Center for Wind Power Drives
DAQ	data acquisition
DC	direct current
DFIG	doubly fed induction generator
DTU	Danmarks Tekniske Universitet
DUT	device under test
DyNaLab	dynamic nacelle testing laboratory
EMPIR	European Metrology Programme for Innovation and Research
EoL	end of line
EPMS	electrical power measurement system
EU	European Union
FhG IWES	Fraunhofer Gesellschaft - Institut für Windenergiesysteme
FVA	Forschungsvereinigung Antriebstechnik e. V.
HiL	Hardware-in-the-Loop
HSS	high-speed shaft
IRIG-B	inter range instrumentation group timecode B
LAS	load application system
LORC	Lindø Offshore Renewables Center
LSS	low-speed shaft
LV	low-voltage
MV	medium-voltage
NTB	nacelle system test bench
NTL	non-torque loading
NTP	network time protocol
PTB	Physikalisch-Technische Bundesanstalt
PTP	precision time protocol
PWM	pulse-width modulation
RPMS	reference power measurement system
RWTH	Rheinisch-Westfälische Technische Hochschule Aachen
SQIG	squirrel cage induction generators
THD	total harmonic distortion
VTT	Technical Research Centre of Finland Ltd.
WindEFCY	Wind efficiency
WP3	Work Package 3
WRIG	wound rotor induction generator



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