88/889/CD

COMMITTEE DRAFT (CD)

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IEC TC 88 : WIND ENERGY GENERATION SYSTEMS	
SECRETARIAT:	SECRETARY:
Denmark	Mrs Christine Weibøl Bertelsen
OF INTEREST TO THE FOLLOWING COMMITTEES:	
FUNCTIONS CONCERNED:	
☐ EMC ☐ ENVIRONMENT ☐ QUALITY ASSURANCE ☐ SAFETY	

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TITLE:

Wind energy generation systems – Part 21-4: Measurement and assessment of electrical characteristics – Wind turbine components and subsystems

NOTE FROM TC/SC OFFICERS:

In order to assist WG 21 when sorting and compiling the given comments on the CD document, it is of great importance that all comments given in the comments form ***refer to both clause and line numbers*** in the CD document

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Information from the project leader to the chapter 9.5 and Annex H (marked with optional) : The subchapter 9.5 and Annex H is a new test procedure on grid forming capabilities of WT subsystems, as there is p.t no fixed requirements on the grid forming control aspects the chapter 9.5 defines the test requirements on the grid forming capabilities, based on the former defined test procedures in this TS. Annex H, provides an informative overview, how the test results can be analysed, mainly based on an existing VDE/ FNN guideline.

As the WG could not agree if these parts should be included in this TS or as a separate TR. The WG would like to have feedback from the NC on the following questions:

1) Shall the grid forming capability tests be included in this TS or should this be developed as separate TR in a later stage?

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WIND ENERGY GENERATION SYSTEMS

Part 21- 4: Measurement and assessment of electrical characteristics – Wind turbine components and subsystems

FOREWORD

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Technical specification IEC TS 61400-21-4 has been prepared by IEC technical committee 88: Wind energy generation systems.

The text of this Technical Specification is based on the following documents:

FDIS	Report on voting
XX/XX/FDIS	XX/XX/RVD

Full information on the voting for the approval of this International Standard can be found in the report on voting indicated in the above table.

This document has been drafted in accordance with the ISO/IEC Directives, Part 2.

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The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under "http://webstore.iec.ch" in the data related to the specific document. At this date, the document will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

The National Committees are requested to note that for this document the stability date is 20XX..

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INTRODUCTION

Grid Code Compliance is a crucial element for Wind Power Plant (WPP) connection to the electrical power system. This compliance process is specified by grid codes, standards and guidelines on international as well as national level. From a Wind Power Plant point of view the single wind turbine (WT) is one element (unit) and consists of several subsystems and components, which supports with its given capabilities to grid compliance aspects. The capabilities of the WPP and WT's are to be verified and validated by defined performance and measurements tests as defined in the IEC 61400-21 series.

The IEC 61400-21 series - Measurement and assessment of electrical characteristics consist of the following standards, technical specifications and technical reports:

- IEC 61400-21-1– Measurement and assessment of electrical characteristics **-** Wind turbine
- IEC 61400-21-2 – Measurement and assessment of electrical characteristics - Wind power plants
- IEC TR 61400-21-3 – Measurement and assessment of electrical characteristics - Harmonic models
- IEC TS 61400-21-4 - Measurement and assessment of electrical characteristics - Wind turbine components and subsystems

Figure 1 gives an overview of the TC 88 standards, in relation to grid connection requirements.

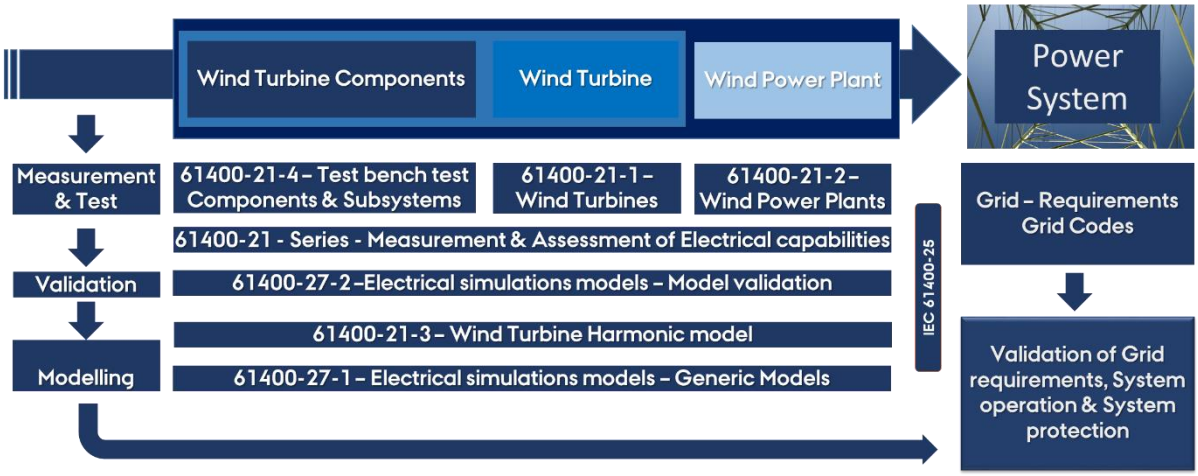

Figure 1 - Overview of TC 88 – Standards related to grid connection

This part IEC TS 61400-21-4 of the IEC 61400-21 series, specifies the test procedures and defines a uniform methodology that standardizes measurement, testing and assessment procedures of electrical characteristics of WT components and subsystems as basis for the verification of the electrical capabilities of WTs and WT families. The results of these component and subsystems test can be used to replace site specific tests as defined in IEC 61400-21-1.

The test & measurement procedures in this technical specification are based on the defined methods and requirements from the IEC 61400-21-1 and defines the same parameters in relation to the validation of the electrical capabilities.

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It defines furthermore additional tests, which are only possible in a controlled test bench environment, such as:

- Voltage capability test
- Voltage dependent reactive power capability tests
- Frequency capability test, RoCoF and phase jump tests
- Harmonic evaluations under ideal conditions
- Grid impedance variations

The procedures as defined in this technical specification provides the basis for detailed simulation model validations and detailed validation of the electrical characteristics of components and subsystems.

This technical specification defines:

- The minimum test setups in relation to the test & measurements of the electrical capabilities in relation to Grid compliance requirements.
- The systems requirements for the test bench to perform these measurements.
- The procedures and related risks for the transferability of test bench components & subsystems test results to Wind turbines and Wind turbines families.
- The documentation and validation requirements for the wind turbine components and subsystems.

The technical specification is a supplement to the IEC 61400-21-1 and IEC 61400-21-2, and does not replace all parts of these standards as there are some functions and performance parameters, which only can be validated on the final product and at the project specific site.

The defined test and measurement procedures can be performed as a combination of functional-, capability-, and performance tests. This TS will be further developed with the increased experience of the defined test procedures as well as the development of test systems, validation procedures and simulation models.

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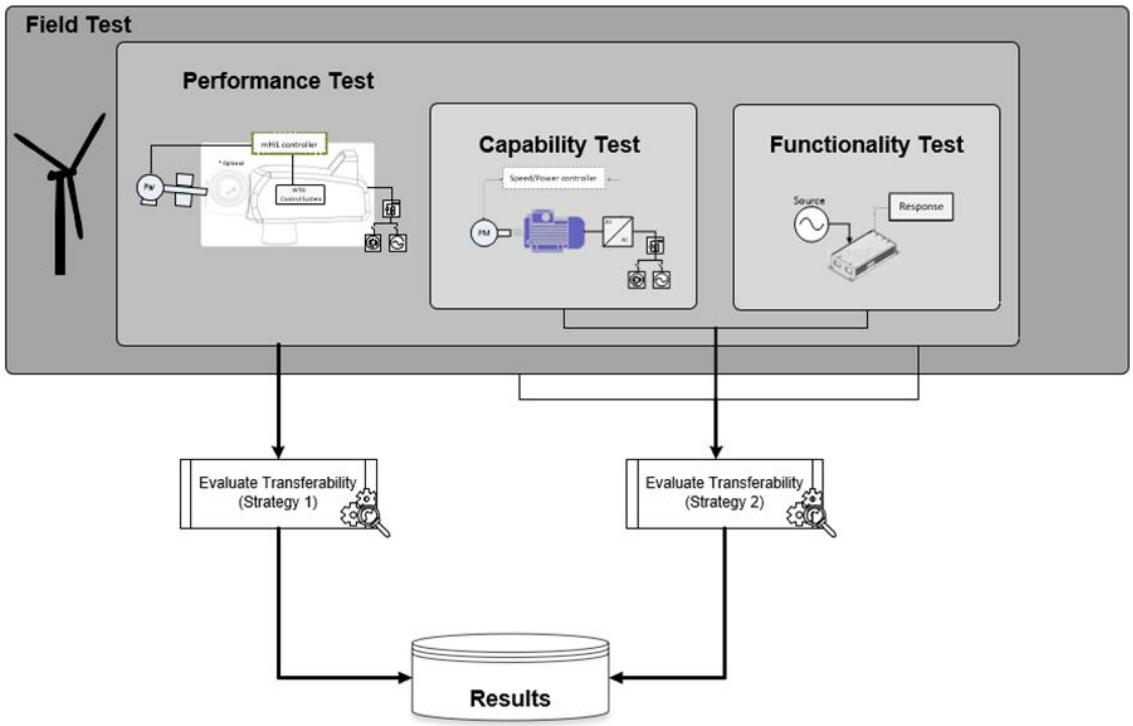

Figure 2 - Overview of functional-, capability-, and performance tests, and there relation to the field tests.

The combination of the different functional-, capability-, and performance tests on subsystem and component level can afterwards, be used to verify the overall performance of the Wind turbine. A detailed test overview and overview of the minimum subsystems, necessary for the verification and assessment of the electrical characteristics are defined in Annex B.

In cases where only minor changes in the subsystems requesting a refresh of certain tests and measurements, or if it has been validated and agreed that the test results are not affected by the different test level, a lower system test level than stated would be acceptable.

The structure of this technical specification is as follows:

Chapter 5: Gives an overview of the required tests, measurements procedures and documentation procedures.

Chapter 6: Defines the minimum setup and the interfaces of the DUT, used for the validation of the different parameters and functions.

Chapter 7: Defines the minimum system requirements and characteristics for the test bench systems to perform these tests of the requested minimum DUT. Furthermore, the overall requirements for the measurement systems. The detailed requirements are defined in the specific chapters.

Chapter 8: Defines the IEC 61400-21-1 specific test in relation to power quality, steady state operation, dynamic response and control performance, as well as the documentation requirements and a risk evaluation for the transferability of the test results towards the WT.

Chapter 9: Defines the optional additional tests, which are only possible in a controlled testbench setup as described in this TS in relation to power quality, steady state operation,

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dynamic response and control performance, as well as the documentation requirements and a evaluation for the transferability of the test results towards the WT.

Annex A: Defines a report template.

Annex B: Provides a detailed overview of the WT components and subsystems, and there influence on the different tests. According to the modular structure defined in the IEC 61400-27-1.

Annex C: Defines the test and validation procedure for the replacement of components.

Annex D: Shows measurement, validation examples and comparisons for the validity of the transferability of test results.

Annex E: Defines exemplary the harmonic assessment methods.

Annex F : Examples of FRT functionality & capability tests.

Annex G: Overview of Hardware in the loop (HiL)systems.

Annex H: Guideline for grid forming control capability tests.

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WIND ENERGY GENERATION SYSTEMS

Part 21- 4: Measurement and assessment of electrical characteristics – Wind turbine components and subsystems

1 Scope

This Technical Specification IEC 61400-21-4 - Measurement and assessment of electrical characteristics - Wind Turbine components & subsystems - specifies a uniform methodology, defining measurement, testing and assessment procedures of electrical characteristics of Wind Turbine components & subsystems, as basis for the verification of the electrical capabilities of Wind Turbines and Wind Turbine families.

The technical specification includes the following aspects:

– Definitions of test bench, subsystems & interface descriptions
– Definitions of system requirements for the test bench to perform these measurements (grid strengths, Sk'', THD,…)
– Measurement procedures for quantifying the electrical characteristics;
– Test & measurements procedures of electrical characteristics of components & subsystems in relation to grid compliance requirements.
– Procedures for the transferability of the component & subsystem test results, measured at the test bench, to WT product families
– Documentation requirements & validation procedures of components, subsystems and Wind turbines

The results of the measurements and assessments of the Wind Turbine components & subsystems will be used as input for the verification of electrical capabilities as described in the IEC61400-21-1 and for the validation & verification of the electrical simulation models for Wind Power Plants (WPP) as described in the IEC 61400-27.

Out of Scope of this technical specification are:

- Design requirements of test bench systems
- Model development of WT subsystems and WT as e.g. described in IEC 61400-27
- Power Plant controls function test (e.g. FSM, Voltage Control) as described in IEC 61400-21-2
- Specific component design test and validation of the Wind turbine equipment (switch- gears, cables, transformer, generator etc., which are covered by other IEC standards
- Mechanical, structural loads & lifetime test
- Noise & acoustical measurements
- Certification procedures & Grid compliance at Wind Power Plant level
- Communication system functional and performance tests as defined in e.g. the IEC 61400-25 series

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139 NOTE

140 For the purposes of this document, the following terms for system voltage apply, based on IEC 60038

141 Low voltage (LV) refers to 100 V < $U_n \leq$ 1 kV;

142 Medium voltage (MV) refers to 1 kV < $U_n \leq$ 35 kV;

143 High voltage (HV) refers to 35 kV < $U_n \leq$ 230 kV;

144 Extra high voltage (EHV) refers to U_n > 230 kV

145

146

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2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC TR 61000-3-6, *Electromagnetic compatibility (EMC) – Part 3-6: Limits – Assessment of emission limits for the connection of distorting installations to MV, HV and EHV power systems*

IEC 61000-4-7:2002, *Electromagnetic compatibility (EMC) – Part 4-7: Testing and measurement techniques – General guide on harmonics and interharmonics measurements and instrumentation, for power supply systems and equipment connected thereto*
IEC 61000-4-7:2002/AMD1:2008

IEC 62008, *Performance characteristics and calibration methods for digital data acquisition systems and relevant software*

IEC 61400-1, *Wind energy generation systems – Part 1: Design requirements*

IEC 61400-21-1: 2019, *Wind energy generation systems – Part 21-1: Measurement and assessment of electrical characteristics – Wind turbines*

IEC 61400-21-2 *Wind energy generation systems – Part 21-2: Measurement and assessment of electrical characteristics – Wind power plants, CDV 2021*

IEC TR 61400-21-3, *Wind energy generation systems – Part 21-3: Wind turbine harmonic model and its application*

IEC 60050-614:2016, *International Electrotechnical Vocabulary – Part 614: Generation, transmission and distribution of electricity – Operation*

IEC 61400-27-1, *Wind energy generation systems - Part 27-1: Electrical simulation models - Generic models*

IEC 61400-27-2, *Wind energy generation systems - Part 27-2: Electrical simulation models - Model validation*

IEC 61400-25-1, Wind energy generation systems - Part 25-1: Communications for monitoring and control of wind power plants - Overall description of principles and models

IEC 60255-181: *Measuring relays and protection equipment – Part 181: Functional requirements for frequency protection*

IEC 60255-151:2009, *Measuring relays and protection equipment – Part 151: Functional requirements for over/under current protection*

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3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at http://www.electropedia.org/
- ISO Online browsing platform: available at http://www.iso.org/obp

3.1
Actuator emulation
Part of the real time HiL controller which simulates the signals and dynamics of missing WT sensors and actuators.

3.1
Auxiliary equipment
equipment that is necessary for setting up all functions and assessing the correct performance (operation) of the DUT (device under test) during the test.

[SOURCE: IEC 61000-4-19, modified: EUT replaced with DUT]

3.2
capability
describes the steady state and dynamic behaviour according of the component or system in relation to the defined parameters.

Note 1 to entry: (e.g. reactive power capability describes the specified steady state capability of the reactive power production or consumption)

Note 2 to entry: e.g. FRT tests showing the specified steady state but also dynamic capability

3.3
capability test
used to assess whether a component or system is able to meet the specifications or requirements against defined parameters as defined in this standard.

3.4
Closed loop control
a type of automatic control in which control actions are based on feedback signals from the controlled equipment or system.

[SOURCE: IEC 62270, ed. 2.0 (2013),modified]

3.5
compliance test
procedure to verify if a characteristic or a property complies with the stated requirements

[SOURCE: IEC 60050, 192-09-02]

3.6
component
A component is defined as the smallest unit were all necessary functions are available in the unit and which cannot be divided into smaller parts without losing the primary function.

NOTE: Examples for wind turbine components are: generators, transformers, switchgear, gearboxes, converters,

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3.7
component test
A component test is defined as a test on a single component, whose necessary functions and required behaviour are not dependent on other components or systems. (e.g. the protection device, if this is an independent unit). A test done on component level shall be valid for all turbine variants where the same component is applied.

3.8
Flicker coefficient for continuous operation
Normalized measure of the flicker emission during continuous operation of the power generation unit or power plant:

$$c(\psi_k) = P_{st,fic} \times \frac{S_{k,fic}}{S_n}$$

Where

c (ψ_k)	is the flicker coefficient of the PGU or PP for continuous operation
$P_{st,fic}$	is the short-term flicker severity from the PGU or PP on the fictitious grid
S_n	is the nominal apparent power of the PGU or PP
$S_{k,fic}$	is the short-circuit apparent power of the fictitious grid

NOTE: The flicker severity for continuous operation is the same for a short-term period (10 min) and a long-term period (2 h).

3.9
Flicker step factor
A normalized measure of the flicker emission due to a single switching operation of the PGU:

$$k_f(\psi_k) = \frac{1}{130} \times \frac{S_{k,fic}}{S_n} \times P_{st,fic} \times T_p^{0,31}$$

where

T_p	is the measurement period, long enough to ensure that the transient of the switching operation has abated, though limited to exclude possible power fluctuations due to turbulence;
$P_{st,fic}$	is the short-term flicker severity from the PGU on the fictitious grid;
S_n	is the nominal apparent power of the PGU;
$S_{k,fic}$	is the short-circuit apparent power of the fictitious grid

NOTE: The short-term flicker severity $P_{st,fic}$ is calculated over the time period Tp.

3.10
functionality
ability to perform a specified operation performed by a component or subsystem and a software program

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Note 1 to entry: Ability to perform a specified operation performed by a component or subsystem and a software program

Note 2 to entry: The activity of performing a function normally employs a system of displays, controls and instrumentation

3.11
functionality test
measurements carried out to test and validate the specified operation of the component or system against selected parameters.

Note: (e.g. Test of different gain factors or protections levels in the component)

Note: Functionally tests are typical done without any power production (e.g. the grid protection test is s typical functionality test)

3.12
fault ride through
FRT
ability of a wind turbine or wind power plant to stay connected during faults in the grid.

Note: The term Fault Ride Through is a general definition for grid faults, in this TS we are using the term FRT only for the under and overvoltage grid fault types and the ability to stay connect under the UVRT and OVRT events

3.13
grid emulator
A programmable AC power supply, capable of emulating various grid conditions to facilitate the testing of grid-connected equipment.

Note: Sometimes also referred as grid simulator.

3.14
grid following control
Control of the grid side converter, where the active and reactive power production follows the reference values.

3.15
grid forming control
Control of the grid side converter in a way that voltage amplitude and frequency are controlled by the converter.

3.16
higher frequency component
Is applied for voltages and currents and is measured and grouped in accordance with Annex B of IEC 61000-4-7:2002/AMD1:2008 (Equation (B1)

3.17

Hardware-in-the-Loop

HiL
A simulation method that allows a hardware under test to interact in a closed loop with a real-time simulation model.

Note: See Annex G for explanations on different variants of HiL

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306 **3.18**

307 **Mechanical-level Hardware-in-the-Loop**

308 **mHiL**
309 HiL where the real-time simulation model interfaces the hardware under test on mechanical
310 level.

311 Note: See Annex G for explanations on different variants of HiL

312 **3.19**
313 **Nacelle**
314 housing which contains the drive-train and other elements on top of a horizontal axis wind
315 turbine tower

316 [Source: IEV 415-01-07]

317

318 **3.20**
319 **negative sequence component of the fundamental**
320 for a three-phase system with phases L_1, L_2 and L_3, the symmetrical sinusoidal three-phase
321 set of voltages or currents having negative frequency the absolute value of which is equal to
322 the fundamental frequency

323 Note 1 to entry: The negative sequence component is defined by the following complex mathematical expression:

324

325 $$\underline{X}_2 = \frac{1}{3}\left(\underline{X}_{L1} + \underline{a}^2 \underline{X}_{L2} + \underline{a}\underline{X}_{L3}\right)$$

326 where $a = e^{j2\pi/3}$ is the 120 degree operator, and X_{L1}, X_{L2} and X_{L3} are the complex expressions of the fundamental
327 frequency phase quantities concerned, that is, current or voltage phasors.

328 Note 2 to entry: Negative sequence voltage or current components may be significant only when the voltages or
329 currents, respectively, are unbalanced. For example, if phase voltage phasors are symmetrical $U_{L1} = Ue^{j\theta}$, $U_{L2} =$
330 $Ue^{j(\theta+4\pi/3)}$ and $U_{L3} = Ue^{j(\theta+2\pi/3)}$ then $U_2 = (Ue^{j\theta} + e^{j4\pi/3}\, Ue^{j(\theta+4\pi/3)} + e^{j2\pi/3}\, Ue^{j(\theta+2\pi/3)})/3 = Ue^{j\theta}\,(1 + e^{j2\pi/3} + e^{j4\pi/3})/3 = 0$

331 [SOURCE: IEC 60050-448:1995, 448-11-28, modified – the term and the definition have been
332 modified and 2 two notes to entry added]

333 **3.21**
334 **no load test**
335 Performance validation of the test equipment, with an open electrical connection to the DUT

336 Note to entry: The test can be done with the main transformer, if this has no impact on the test equipment setup and
337 results. The setup needs to be stated in the test report

338 **3.22**
339 **nominal apparent power**
340 apparent power from the wind turbine while operating at nominal current and nominal voltage
341 and frequency:

342 $S_n = \sqrt{3} U_n I_n$ at Q =0

343 where

344 U_n is the nominal voltage;

345 I_n is the nominal current

346 **3.23**
347 **nominal current (for wind turbines)**
348 nominal value I_n of wind turbine current, which are calculated from nominal active power P_n

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and nominal voltage U_n according to $I_n = \frac{P_n}{\sqrt{3}U_n}$;

3.24 3
nominal active power
nominal value of wind turbine active power, which are stated by the manufacturer and is used as per-unit base for all powers (active, reactive, apparent)

3.25
overshoot
difference between the maximum value of the response and the steady state final value

Note 1 to entry: See Figure 3.

3.26
open loop
A form of control without feedback

[SOURCE: IEC 62270, ed. 2.0 (2013)]

3.27
over voltage ride through
OVRT
ability of a wind turbine or wind power plant to stay connected during voltage swells

Note 1 to entry: In some publications, the expression “High Voltage Ride Through (HVRT)”, is used for the same event.

3.28
performance
describes the steady state and dynamic fulfilment according to the specification of the complete system in relation to the defined parameters

3.29
performance test
Measurements and tests carried out to determine the ability of the DUT against selected parameters to achieve an intended function.

Note to entry: The test intends to validate the performance of the control system on the complete system - DUT -, including all subsystems and components, which has a significant influence on the overall performance of the function.

3.30
phase jump
Rapid change in the phase angles of the supply voltage

Note: The phase jump test could be a requirement from the grid codes and defines that the DUT must be able to withstand a transitory phase jump without disconnection

3.31
phase shift (IEC Glossary)
Defined as:

a) the absolute magnitude of the difference between two phase angles

b) the displacement in time of one periodic-waveform relative to other waveforms

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3.32
Power Hardware-in-the-Loop
PHiL
HiL where the real-time simulation model interfaces the hardware under test on electrical (power) level.

Note: See Annex G for explanations on different variants of HiL

3.33
positive sequence component of the fundamental
for a three-phase system with phases L1, L2 and L3, the symmetrical sinusoidal three-phase set of voltages or currents having positive frequency equal to the fundamental frequency. The positive sequence component is defined by the following complex mathematical expression:

$$\underline{X}_1 = \frac{1}{3}\left(\underline{X}_{L1} + \underline{a}\underline{X}_{L2} + \underline{a}^2\underline{X}_{L3}\right)$$

where $\underline{a} = e^{j2\pi/3}$ is the 120 degree operator, and $\underline{X}_{L1}$, $\underline{X}_{L2}$ and $\underline{X}_{L3}$ are the complex expressions of the fundamental frequency phase quantities concerned, that is, current or voltage phasors

Note 1 to entry In a balanced harmonic-free system, only positive sequence component of the fundamental exists. For example, if phase voltage phasors are symmetrical $U_{L1} = Ue^{j\theta}$, $U_{L2} = Ue^{j(\theta+4\pi/3)}$ and $U_{L3} = Ue^{j(\theta+2\pi/3)}$ then $U_1 = (Ue^{j\theta} + e^{j2\pi/3}\,Ue^{j(\theta+4\pi/3)} + e^{j4\pi/3}\,Ue^{j(\theta+2\pi/3)})/3 = (Ue^{j\theta} + Ue^{j\theta} + Ue^{j\theta})/3 = Ue^{j\theta}$.

[SOURCE: IEC 60050-448: 448-11-27:1995, modified – the term and the definition have been modified and Note 1 to entry has been added]

3.34
Q-capability
reactive power capability of a wind turbine, which is measured from the capability curve or by a site-specific test or defined from the manufacturer

3.35
quasi steady state of a system
short-term steady state, for instance during a voltage dip or voltage swell which is long enough to include a period where the system state variables can be considered sensibly constant. (Source IEC 61400-27-2)

3.36
ramp-down time
time during which the measured value decreases from 90 % to 10 % of the target value

3.37
reaction time
elapsed time from test command issued until the change in amplitude reaches 10 % of the measured output variable of the step height

Note 1 to entry: See Figure 3

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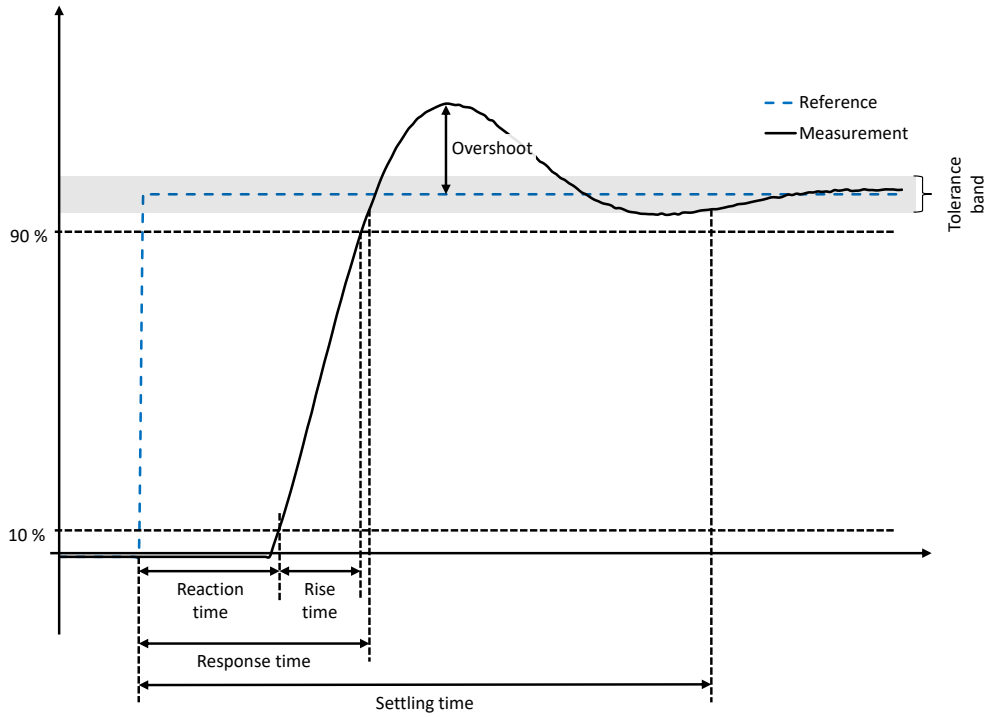

Figure 3 – Example of step response

3.38
recovery time
time from end of the event after which the measured value is continuously within the predefined tolerance band around the start value before the event.

3.39
response time
time from the start of event until the observed value enters for the first time the defined steady state tolerance band.

Note 1 to entry: See Figure 3

3.40
rise time
time from the observed value reached 10 % of the step change until the observed value reaches 90 % of the step change.

Note 1 to entry: See Figure 3

3.41
rotor emulation
Real time system that simulates the wind field, Wind turbine rotor and drivetrain components for mHiL operation.

3.42
settling time
time defined as the elapsed time from the issue of a step change command until the observed value continuously stays within the predefined tolerance band of the target value.

Note 1 to entry: See Figure 3

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3.43
short-circuit apparent power (IEV 601-01-14)
The product of the current in the short circuit at a point of a system and a conventional voltage, generally the operating voltage.

Note: Short-circuit currents and short-circuit impedances may also be determined by system tests. For converter-based grid emulator, the steady state short circuit power S_k can be determined by measuring the voltage variation ΔU in response to power variations.

3.44
short-circuit impedance
equivalent impedance at the fault location.

Note: The calculation of the short-circuit impedance is generally based on the rated data of the electrical equipment and the topology of the grid.

3.45
short-circuit ratio *SCR*
ratio of the short circuit apparent power S_k to the nominal power S_n

$$SCR = \frac{S_k}{S_n}$$

3.46
source
electric power supply to feed signals or energy into electrical system or controller.

3.47
start of event
time instant where the stimulus value deviates for the first time outside its defined stimulus tolerance band.

Note 1 to entry: Stimulus may be a reference signal or a disturbance.

Note 2 to entry: Default stimulus tolerance band is defined to be ± 10 % of the stimulus increment and centred on the value the stimulus had before the event.

3.48
static error
deviation between the obtained values compared to a requested reference value.

3.49
steady state
status of the system obtained when the settling time has expired.

3.50
sub-group
Grouping method according to IEC 61000-4-7/AMD1:2008. Sub-grouping is used for integer sub-grouped harmonic currents and voltages and for interharmonic centered sub-group currents and voltages.

3.51
sub-group total harmonic current distortion - THC (symbol)
ratio of the r.m.s. value of the harmonic sub-groups (I_h) to the r.m.s. value of the sub-group

associated with the nominal current (U_n):

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$$THC = \sqrt{\sum_{h=2}^{50} \left(\frac{I_h}{I_n}\right)^2}$$

3.52
sub-group total harmonic voltage distortion - *THDSU$_n$* (symbol)

ratio of the r.m.s. value of the harmonic sub-groups (U_h) to the r.m.s. value of the sub-group associated with the nominal voltage (U_n):

$$THDS_{Un} = \sqrt{\sum_{h=2}^{hmax} \left(\frac{U_h}{U_n}\right)^2}$$

NOTE: In this standard the value of h_{max} is either 50 or 180 as given in the specific requirements.

3.53
sub-system
A portion of a system which fulfils a specific function, consisting of several components/elements, which are directly related to each other and are directly interacting for the defined function.

3.54
sub-system test
test on a sub-system, where all necessary functions and performance for the test are available in the sub-system and are not dependent on other components or systems.

Note 1 to entry: Test done on a sub-system is valid for all turbine variants, where the sub-system is used.

3.55
tolerance band
acceptable deviation range of the measured signal from the defined target value.

Note 1 to entry: The steady state target value is usually defined to be equal to the observed signal's reference value or the value towards which the observed signal is converging after the event.

Note 2 to entry: Default tolerance band is defined to be ± 10 % of the nominal value if nothing else is stated

3.56
validation
confirmation, through the provision of objective evidence, that the requirements for a specific intended use or application have been fulfilled.

Note: In relation to this TS, the defined test & measurement procedures are validation procedures as the validation is based on experimental data in relation to an intended use.

Note: In this TS the defined tests procedures etc. are validation tests, as the TS does not verify that specific requirements are meet.

[Source: IEV 192-01-18, modified]

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3.57

verification
confirmation, through the provision of objective evidence, that specified (system) requirements have been fulfilled.

Note: In in relation to this TS the measurement results can be used to assess conformity of a design to a specified requirement e.g. verify that the system fulfils e.g. specific grid code requirements.

3.58
voltage dip
limited duration non-periodic sudden decrease of the power supply network's voltage magnitude and associated change of its phase.

Note 1 to entry: In some articles, publications, etc. the expression "voltage sags" is used for the same event.

3.59
voltage swell
limited duration non-periodic sudden increase of the power supply network's voltage magnitude above its nominal value and associated change of the phase of the voltage.

3.60
unbalance factor
in a three-phase system, the degree of unbalance expressed by the ratio $\left|\underline{X}_2 / \underline{X}_1\right|$ (in percent) between the values of the negative sequence component $\underline{X}_2$ and the positive sequence component $\underline{X}_1$ of voltage or current.

[SOURCE: IEC 60050-614:2016 614-01-33,]

3.61
under voltage ride through
UVRT
ability of a wind turbine or wind power plant to stay connected during voltage dips.

NOTE 1 to entry: In some publications, the expression "Low Voltage Ride Through (LVRT)", is used for the same event.

3.62
wind turbine terminals
WTT
point that is part of the WT and identified by the WT manufacturer as a point at which the WT may be connected to the power collection system.

3.63
zero sequence component of the fundamental
for a three-phase system with phases L1, L2 and L3, the in-phase sinusoidal voltage or current component having the fundamental frequency and equal amplitude in each of the phases.

Note 1 to entry: The zero sequence component is defined by the following complex mathematical expression:

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$$\underline{X}_0 = \frac{1}{3}\left(\underline{X}_{L1} + \underline{X}_{L2} + \underline{X}_{L3}\right)$$

where $\underline{X}_{L1}$, $\underline{X}_{L2}$ and $\underline{X}_{L3}$ are the complex expressions of the fundamental frequency phase quantities concerned, that is, current or voltage phasors

[IEC 60050-448:1995, 448-11-29, modified – the term and the definition have been modified and the note to entry added]

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4 Symbols and abbreviations

In this part of IEC 61400, the following symbols and units are used.

Symbols (The final update will be done together with the CDV)

ψ_k	network impedance phase angle (°)
$\alpha_m(t)$	electrical angle of the fundamental of the measured voltage (°)
$c(\psi_k)$	flicker coefficient for continuous operation
d	relative voltage change (%)
d_c	steady-state voltage change as defined in IEC 61000-4-15
d_{max}	maximum voltage change
f_g	nominal grid frequency (50 Hz or 60 Hz)
$f_{inertia,\ recovery}$	frequency threshold where the turbine shall stop boosting active power (Hz)
$f_{inertia,\ trigger}$	frequency threshold where the turbine shall start boosting active power (Hz)
f_{over}	overfrequency protection level (Hz)
f_{under}	underfrequency protection level (Hz)
h	harmonic order
$I_{h,i}$	h^{th} order harmonic current distortion of i^{th} wind turbine (A)
$i_m(t)$	measured instantaneous current (A)
I_n	nominal current (A)
IUF	current unbalance factor
P	active power (W)
P_{lt}	long term flicker severity
P_n	nominal active power of the power plant (W)
P_{st}	short term flicker severity
Q	reactive power (var)
S_k	short-circuit apparent power of grid (VA)
$S_{k,fic}$	short-circuit apparent power of the fictitious grid (VA)
S_n	nominal apparent power (VA)
T_p	transient time period of a switching operation (s)
U	phase-to-phase voltage (V)
U_n	nominal phase-to-phase voltage (V)
U_{under}	undervoltage protection level (V)
U_{over}	overvoltage protection level (V)
U_{pre}	pre-fault voltage (V)
UUF	voltage unbalance factor

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Abbreviations

A/D converter	analogue-to-digital converter
Aux.	Auxiliary equipment
DFAG	doubly-fed asynchronous generator (Often referred to as a doubly-fed induction generator (DFIG), but it is not operated as an induction generator when the rotor current is controlled.)
DFT	Discrete Fourier Transformation
DUT	Device under test
FRT	Fault ride through
HiL	Hardware in the loop
HSS	High Speed Shaft
HV	High voltage
HW	Hardware
LSS	Low Speed Shaft
LV	Low voltage
mHiL	mechanical Hardware in the loop
MP	Measurement Point
MV	Medium voltage
OVRT	Overvoltage ride-through
PGU	Power generation unit
PHiL	Power Hardware in the loop
PM	Prime Mover (motor)
POC	Point of connection
PPC	power plant controller
RMS	root mean square

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RoCoF	rate of change of frequency
RPM	Revolutions per minute
SCADA	supervisory control and data acquisition
SW	Software
THC	total harmonic current distortion
UVRT	Undervoltage ride-through
WLU	Wind Load Unit
WT	Wind Turbine
WTT	Wind Turbine Terminals

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5 Overview of tests

Table 1 gives an overview of the minimum required test levels for the different tests and measurements as described in this TS - Technical Specification, as well as the minimum recommended requirements for the test system, where the DUT / WT is connected to.

Note: The required test bench system, is always referring to the minimum required system. That means, if a higher test bench system is used the other levels are automatically included (e.g a test bench system Figure 5 1a, can as well be used for tests requiring a test bench system in Figure 5 2a or 2b).

Table 1 - Overview of tests according to chapter 8

Chapter	Test	Test level - DUT	Minimum Test bench system (c.f. Chapter 7)	Comment
Power Quality Aspects				
8.1.1	Flicker	WT	Field test	
8.1.2	Flicker and voltage change during switching operations	WT	Field test	
8.1.3	Harmonics	Subsystem	2b	
Steady State				
8.2.1	Maximum power	Subsystem	1a	
8.2.2	Reactive power characteristic (Q=0)	Subsystem	2b	
8.2.3	Reactive power capability	Subsystem	2b	
8.2.4	Voltage dependency of PQ diagram	Subsystem	2b	
8.2.5	Unbalance factor	Subsystem	2b	
Control performance				
8.3.1	Active power control	Subsystem	1a	
8.3.2	Active power ramp rate limitation	Subsystem	2a	
8.3.3	Frequency control	Subsystem	2b	
8.3.4	Synthetic inertia	Subsystem	1a	
8.3.5	Reactive power control	Subsystem	2b	
Voltage fault ride through				
8.4.2	FRT - Performance testing according to Strategy 1	Subsystem	1a to 3a	Depending on the test category
8.4.3	Functionality and Capability testing according to Strategy 2	Subsystem	1a to 3a	Depending on the test category
Grid Protection				

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8.5.1	Grid protection	Component/ Subsystem	3c	Functionality test of protection system on component level
8.5.2	Rate of change of frequency RoCoF (df/dt)	Component/ Subsystem	3c	Functionality test of protection system on component level
8.5.3	Reconnection time	WT	Field test	

Table 2 shows the additional tests, which are specified in this technical specification, as these tests are typical performed on a controllable test bench setup.

Table 2 - Overview of tests according to chapter 9

Chapter	Test case	Test level - DUT	Test bench system	Comment
Power Quality Aspects				
0	Flicker control	Subsystem	1b	
9.1.2	Flicker and voltage change during switching operations	Subsystem	2b	
9.1.3	Active filter / Sink for harmonics	Subsystem	2b	
9.1.4	Impedance measurements	Subsystem	2b	
Steady State				
9.2.1	Voltage capability	Subsystem	2b	
9.2.2	Frequency capability	Subsystem	2b	
9.2.3	Current Unbalance Factor in an unbalanced system	Subsystem	2b	
Control performance				
9.3.1	Grid Impedance variations	Subsystem	1b	
9.3.2	Island operation	Subsystem	1b	
Dynamic performance				
9.4.1	RoCoF – real df/dt – capability	Subsystem	1b	
9.4.2	Phase jump	Subsystem	1b	

A different system level than stated would be acceptable, in cases where minor changes in the subsystems are requesting a refresh of some tests & measurements, or if it has been validated and agreed that the test results are not affected by the different test level. A more detailed guideline in relation to the replacement of components is given in Annex C and a detailed description of the test bench levels are given in Annex B.

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6 Definitions of minimum DUT, components and subsystems

6.1 General

The following chapter defines the minimum test setup of the DUT and the interfaces of the DUT, which are recommended for the validation of the described tests.

Furthermore, this chapter defines the different components and subsystems, as well as the controller functionalities, which are responsible for the performance of the different electrical capabilities and control features.

The structure follows the modular structure as defined in IEC 61400-27-1.

6.2 Description of components and subsystems

Figure 4 gives an overview of the main components, subsystems and control functions as well as the main input and output parameter, which have an influence in relation to the different test and measurement procedures as described in this technical specification.

Note: As an example: For the reactive power capability measurement the subsystems: power conversion system and electrical connection (including the WT type specific components) are influencing the reactive power capability measurements and shall be represented in the DUT. The responsible control system is the grid power control (reactive power control) and shall as well be part of the test setup.

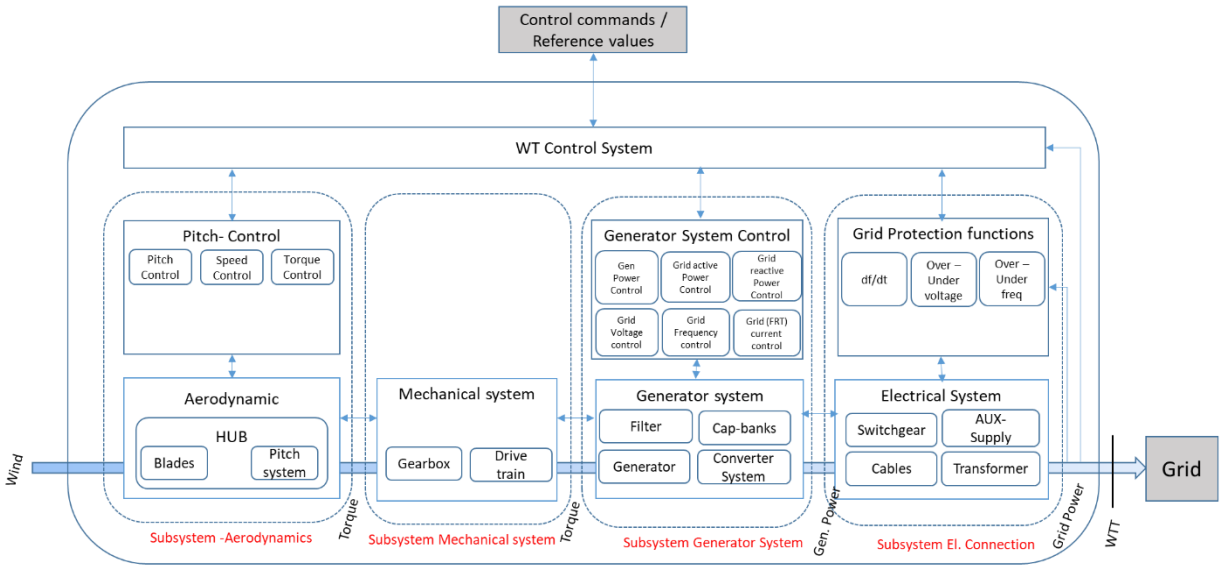

Figure 4 – Generic structure of WT

Depending on the WT type some of the following main components will be part of the different subsystems for the different WT types.

Subsystem	Main Components	Description
Aerodynamics	Blades	Blades of the WT
	Pitch System	Mechanical / electrical system to rotate the blades
	HUB	fixture for attaching the blades assembly to the rotor shaft
	Control functions	

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	Pitch Control	Control system to control the pitch angle of the blades
	Speed control	Control system to control the rotational speed of the main shaft
	Torque control	Control system to control the torque to the main shaft

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Subsystem	Main Components	Description
Mechanical System	Gearbox	Gearbox
	Drive system	Mechanical drive train - main shaft bearings etc.
	Bearings	

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Subsystem	Main Components	Description
Generator system	Generator	Generator of the WT – depending on the Type Asynchronous, synchronous, DFIG, etc.
	Converter	Converter system for the Type III and type IV WT
	Filter	Filter system for switch harmonics etc.
	Control functions	
	Gen power control	Active and reactive power control of the power conversion system
	Grid active power control	Active power control of the grid side system
	Grid reactive power control	Reactive power control of the grid side system
	Grid voltage control	Grid voltage control functions
	Grid frequency control	Grid frequency control functions
	Grid (FRT) Current Control	Current control during fault ride through events

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Subsystem	Main Components	Description
Electrical connection	Transformer	LV to MV transformer
	Cables	Tower cables etc.
	Switchgear	Protection device
	Aux-supply	Supply of the Auxiliary equipment in the WT
	Grid Module	Grid measurement module
	Cap-banks	Reactive power compensation e.g. for type I and type II
	Grid Protection functions	
	Frequency protection	Over and under frequency protection
	Voltage protection	Over and under voltage protection
	df/dt	RoCoF protection

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The detailed description about the operating and test conditions are defined in the respective chapters of this specification. In Annex B, are the different components and subsystems listed together with the control functionalities, in relation to the different measurement and test procedures, as described in this TS in relation to the different turbine types etc.

7 Test bench systems

7.1 General for test Benches

To test electrical characteristics of the wind turbine, test benches of different system levels and of different complexities can be used. The following chapters describe different test benches including requirements to obtain valid test results from functionality, capability and performance testing, when measuring the electrical characteristics.

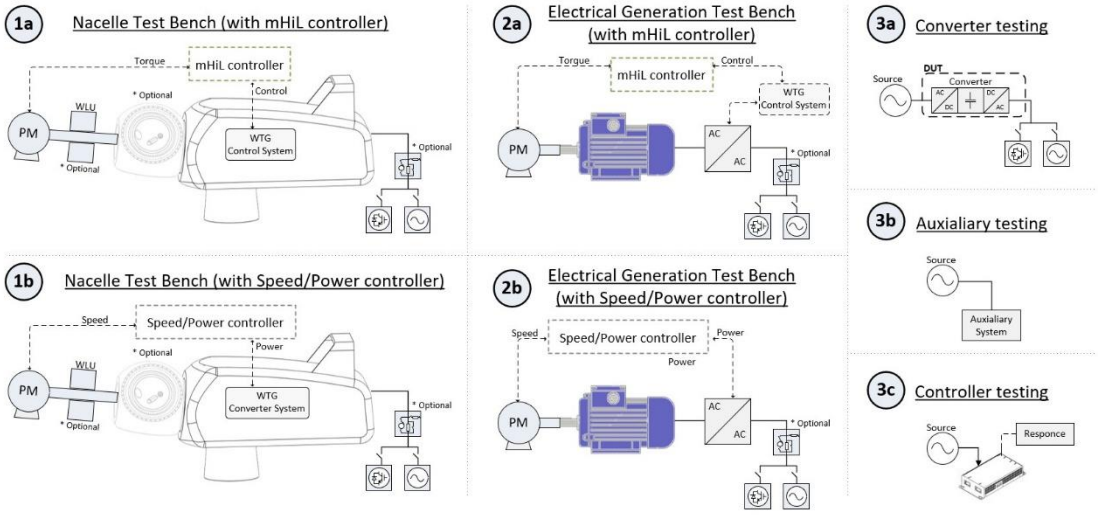

Figure 5 - Examples of Nacelle Test Benches type 1a, 1b to the left. Examples of Electrical Generation Test Benches type 2a, 2b in the middle and examples of component test benches type 3a, 3b, 3c to the right.

7.2 Nacelle test bench type (1a) and (1b)

Generally when referring to Nacelle Test Benches, the complete nacelle is placed on the test bench and the different components of the wind turbine (e.g. generator, gearbox, hydraulics, main bearing(s) and electrical cabinets) are mounted in the nacelle in its original positions and structures. Hereby, the wind turbine's control system is in operation and the load of the different electrical systems is equivalent to site operation.

If parts of the electrical systems are located in or outside the tower section of the turbine, these components can be placed next to the test bench, in its original mechanical structure and frames etc. This ensures correct interfaces and electrical cable lengths as well as electrical noise properties, which enables valid test results for performance testing.

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7.2.1 Nacelle test benches with mHiL controller (1a)

Nacelle test benches are distinguished by two different operation modes. Namely, these are 1a: “Nacelle testing with turbine control system in mHiL mode”, c.f. Figure 6 and mode 1b: “Nacelle testing in torque/speed mode”, c.f. Figure 7.

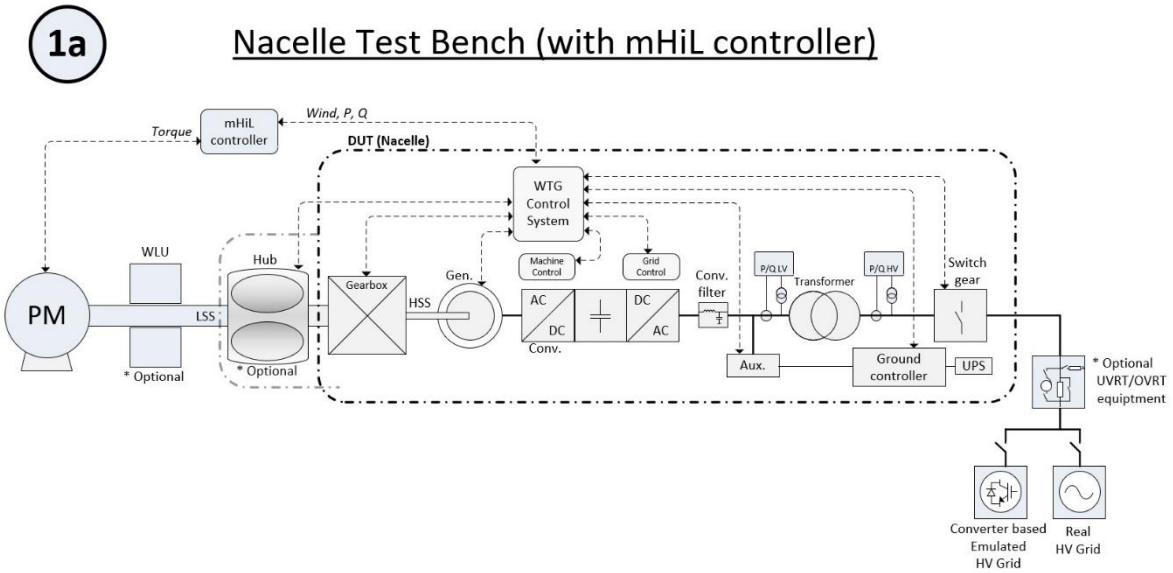

Figure 6 – Example of Nacelle Test Bench in mHiL control mode (1a)

Note: If the hub is part of the test setup, and the pitch system of the turbine is operational, a more simplified mHiL control mode can be implemented to achieve the correct operational dynamic response of the turbine during testing. With verified parameters of the rotor characteristic of the tested WT (wind, pitch angle, RPM, resulting torque) and an inertia compensation, the dynamic response can be obtained by controlling the prime mover in torque control mode. Therefore performance testing is also possible in this mode.

Note: This type of test bench is typically used for performance testing of the complete system or functionality and capability testing of individual components and sub-systems.

The mHiL controller itself is described in more details in chapter 7.5.1.

The prime mover (PM) is described in chapter 7.5.2.

The UVRT/OVRT equipment is described in chapter 7.5.3.

In the mHiL mode (1a) all the WT’s control systems are active during testing, and the response to the electrical tests are representative to real site operation, because the mHiL controller ensures correct dynamic response of the turbine and its control systems torque/speed wise. As described in more detail in 7.5.1, this is done with the help of an emulation of the aerodynamic and mechanic properties of the rotor, the tower and missing actuators.

Furthermore, all the electrical systems that will experience the grid event are present and operational in the type 1a nacelle test bench. This makes it possible to do performance testing, which is equivalent to site tests, and can therefore replace site test campaigns.

The grid side-converter of the DUT can be connected either to a real grid or to a grid emulator. The grid emulator is described in chapter 7.5.3.2.

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7.2.1.1 Requirements on Nacelle Test Benches (1a)

In order to achieve results equivalent to site tests, the mHiL operation must be validated. It can be by performing a number of tests with varying wind speeds / wind speed ramps to compare test bench measurements with site measurements or results derived with reliable load simulation models.

The tested wind turbine is operated with its original control system software. No changes to relevant control software are permitted.

If parts of the electrical system are left out of the tests (e.g. yaw or pitch) they must be tested separately in order to validate the performance of the final nacelle design.

7.2.2 Nacelle Test Benches in Speed / Power mode (1b)

If the test does not require a correct dynamic speed response of the DUT or that the DUT operates according to its characteristic power/speed curve, the prime mover can be operated in speed/power control mode without mHiL, as illustrated in Figure 7.

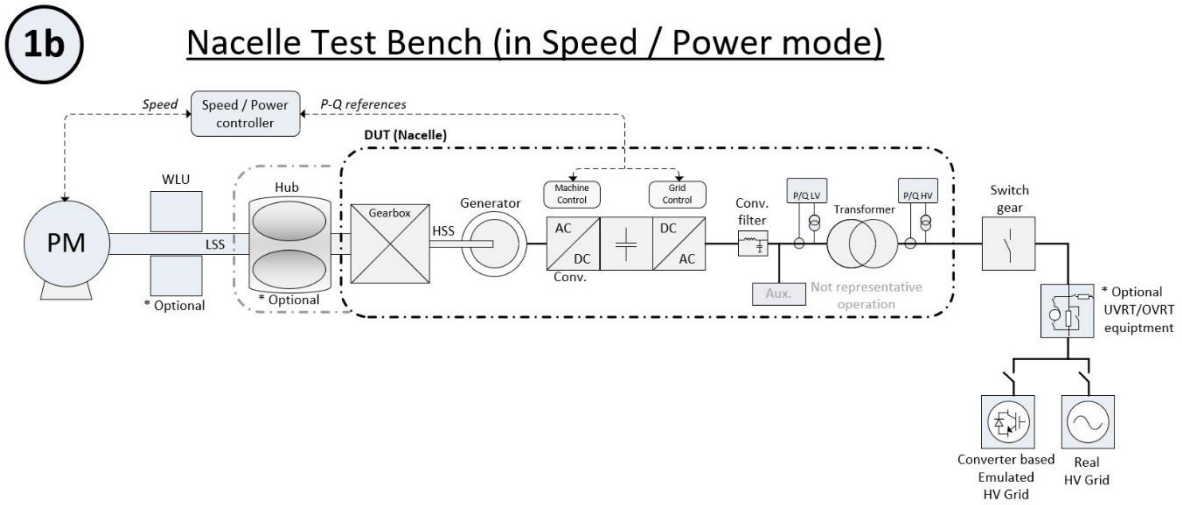

Figure 7 - Example of Nacelle Test Bench in Speed / Power control mode (1b)

Note: This type of test bench is typically used for functionality and capability testing of individual components and sub-systems.

In this mode functionality testing and capability testing is possible, to verify that the different systems comply with the requirements.

The test setup is controlled with a speed and a power controller, which are setting speed references to the prime mover converters, and active as well as reactive power references to the DUT grid side converter. With that, specific load situations in terms of speed, active and reactive power can be configured and tested. In this test bench configuration, the WT controller and auxiliary systems are not active during testing and therefore the dynamic response, electric performance, and protections are not representative for real on-site operation.

7.2.2.1 Requirements for Nacelle Test Benches (1b)

In order to verify functionality and capability of the different turbine electrical systems (e.g. converter, filters and generator) the nacelle test bench can be operated in Speed/Power mode.

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707 The test bench’s speed or power controller must be able to set desired references with sufficient
708 accuracy. The dynamics of the speed/power controller must be sufficient for planned tests.
709

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7.3 Electrical generation test bench (2a) and (2b)

An Electrical Generation Test Bench includes only selected components of the WT's drive train in the test setup. Especially mechanical components of the drive train, such as gearbox, main bearing, and corresponding auxiliaries are not included in this test setup. This may cause some variation of the test results compared to results derived on a Nacelle Test Bench but reduces test time preparation and minimized test costs.

7.3.1 Electrical generation test bench with mHiL mode (2a)

Electrical Generation Test Benches are also distinguished by two different operation modes. Namely, these are 2a: "Electrical Generation Test Bench with turbine control system in mHiL mode", c.f. Figure 8 and mode 2b: "Electrical Generation Test Bench in Speed / Power mode", c.f. Figure 9.

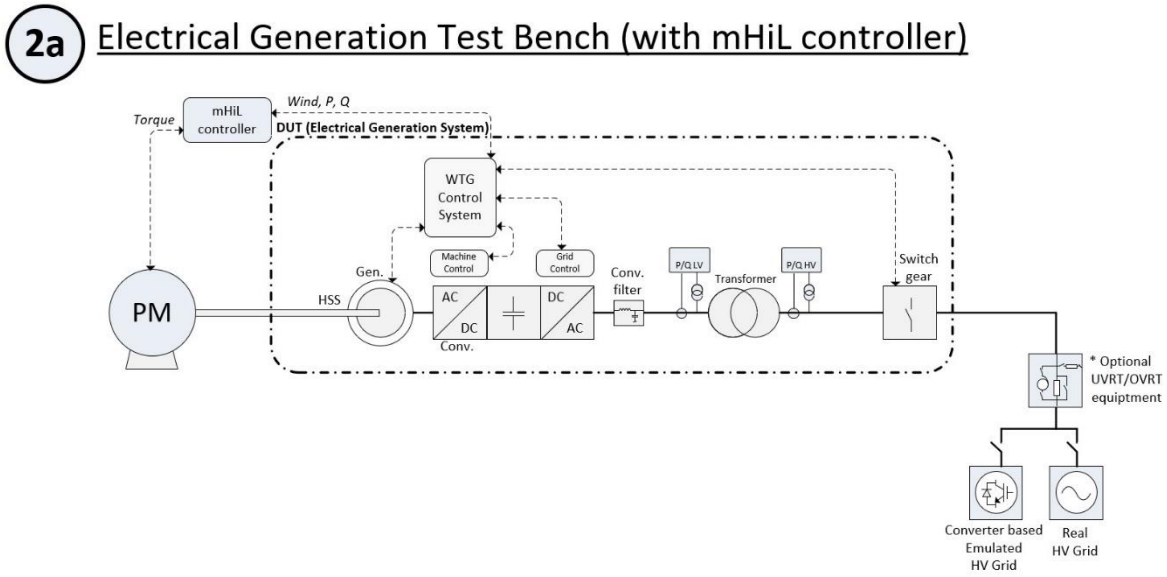

Figure 8 - Example of Electrical Generation Test Bench in mHiL control mode (2a)

Note: This type of test bench is typically used for functionality and capability testing of individual components and sub-systems, as the test setup does not include the auxiliary systems such as lubrication, fans and its protection systems.

In mHiL mode (Figure 8) the DUT at the Electrical Generation Test Bench is operated with its original control software alongside with the mHiL-controller. The mHiL controller emulates the dynamic speed response of the wind turbine observed in the field at the test bench. With that, the DUT on the test bench is characterized by the same dynamic speed response as the corresponding wind turbine in the field.

The mHiL controller itself is described in more details in chapter 7.5.1. Compared to the mHiL controller used for Nacelle Test Benches, it features an additional simulation model to emulate the impact of the missing mechanical drive train components.

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7.3.1.1 Requirements for electrical generation test benches(2a)

The wind turbine is operated with its original control software with minimum changes. The mHiL-System must be validated against proven simulation models or field data. The test bench's control system must be capable of applying mechanical loads as dynamically as required by the mHiL-System.

7.3.2 Electrical generation test bench (2b)

If the test bench does not have a mHiL controller and DUT does not have complete WT control system, then the tests can be conducted in a Speed/Power mode following pre-set speed and power references. As for the Nacelle Test Bench in Speed / Power mode (c.f. section 7.2.2) the test setup is controlled by a speed / power controller as illustrated in Figure 9. These controllers are setting the speed references for the prime mover converter as well as the active and reactive power references for the WT converter.

As the WT control is not operating, the dynamic speed response is not representative for real on-site operation. Consequently, in this mode only functionality and capability testing, is possible.

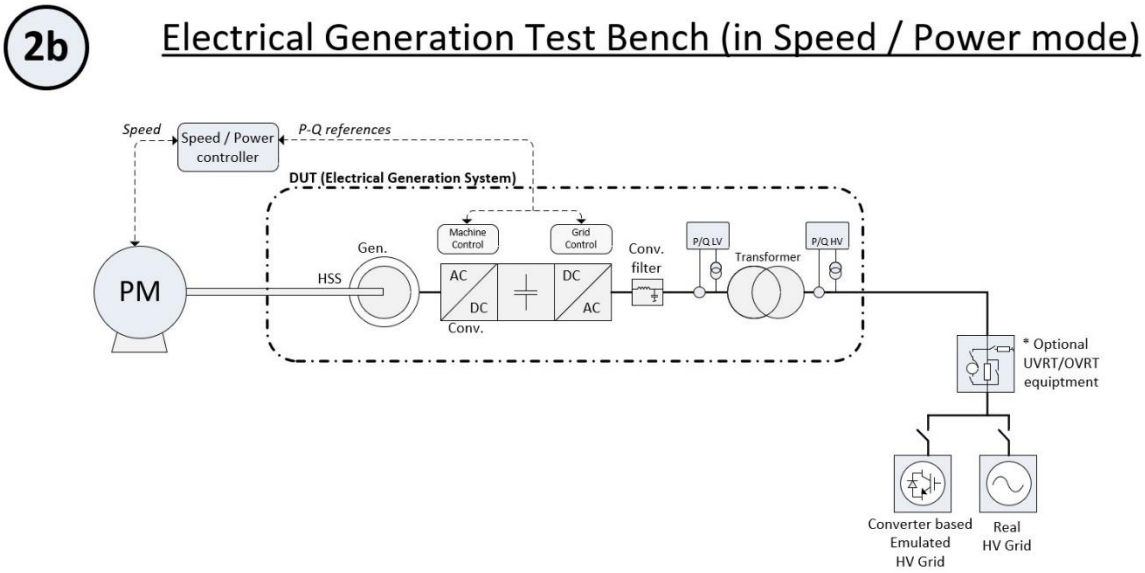

Figure 9 - Example of electrical generation test bench in speed / power control mode

Note: This type of test bench is typically used for functionality and capability testing of individual components and sub-systems.

7.3.2.1 Requirements for electrical generation test benches (2b)

Changes to the wind turbine control software are acceptable if they do not influence the results of the planned test. The test bench's speed or torque controller must be able to set desired references with sufficient accuracy. The dynamic of the speed/power controller must be sufficient for planned tests.

Chapter 7.5 provides more requirements for the test bench equipment.

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7.4 Component test benches

To test the functionality of the different components and sub-systems in the turbine, dedicated component test benches can be used.

Some examples of different component test benches are described in the following sections.

7.4.1 Converter test bench (3a)

An electric source can be used to load the machine-side converter to have power flow through the converter. The source will act electrically as the generator in the wind turbine.

The grid-converter can be connected either to a real grid or alternative to a grid emulator to verify the functionality and capability of the converter system as illustrated in Figure 10.

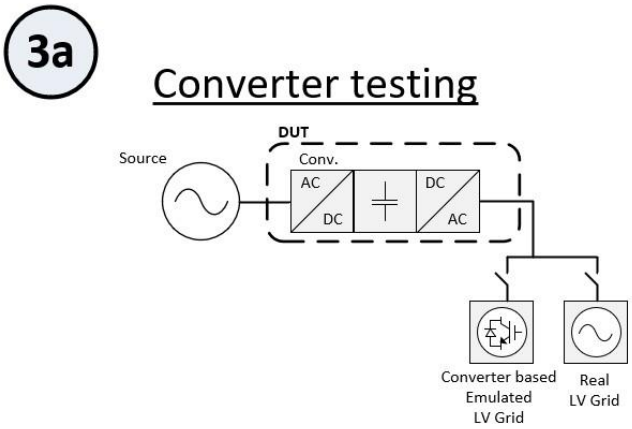

Figure 10 - Example of Converter Test Bench (3a)

Note: This type of test bench is typically used for functionality and capability testing of individual components and sub-systems.

This component test bench can be used for testing of the converter system as a stand-alone system.

7.4.1.1 Requirements for converter test bench (3a)

To achieve valid results from the tests, the DUT converter including filter and chopper components must be equivalent to the ones used in the WT.

7.4.2 Auxiliary test bench (3b)

To verify the functionality of the auxiliary system(s) of the turbine, the different electrical systems can be connected to an electric source which can replicate the grid events etc.

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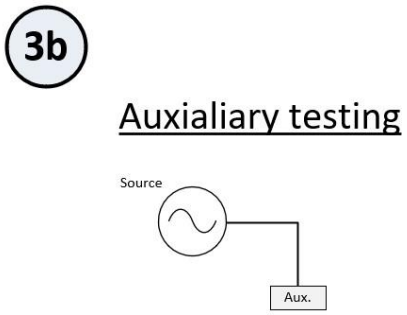


781

782 **Figure 11 - Example of auxiliary test bench (3b)**

783 Note: This type of test bench is typically used for functionality and capability testing of individual components and
784 sub-systems.

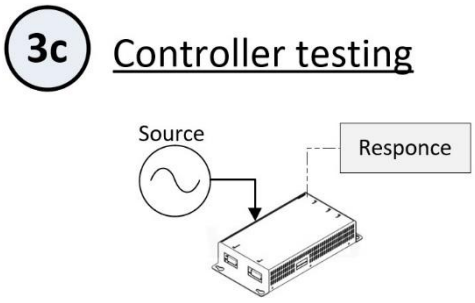
785 Depended on the test to be executed the test bench must be designed to load the Auxiliary
786 equipment to gain valid results.

787 **7.4.2.1 Requirements for auxiliary test bench (3b)**

788 To achieve valid results, the Auxiliary equipment must be loaded under worst case operating
789 conditions, meaning fans, pumps, lubrications systems and its control systems must operate
790 with the right pressure, temperature and vibration levels.

791 **7.4.3 Controller test bench (3c)**

792 To perform a functionality test on the individual controllers for the WT a controller test bench
793 can be used. For this, the WT original control software is operated on the original controller
794 hardware, i.e. the real combination of software and hardware is considered the DUT. The
795 controller test bench includes several simulations (c.f. Figure 13 or Figure 14), which allow to
796 provide any required signals (e.g. voltage and currents) to the tested WT controller and its
797 response e.g. to electrical events can be observed.



798

799 **Figure 12 - Example of controller test bench (3c)**

800 Note: This type of test bench is typically used for functionality testing of individual components.

801 Depending on the architecture of the controller and its integration into the overall system, the
802 test bench operates the controller in:

803 • Open loop control or

804 • Closed loop HiL control (HiL setup)

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805 The following pictures show a more detailed representation of the test benches.

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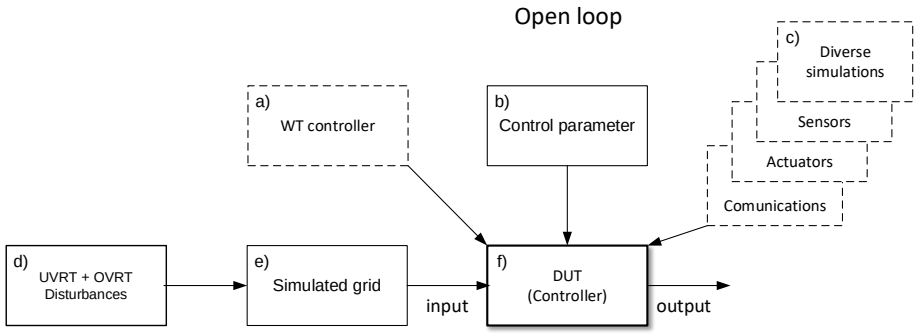

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808 **Figure 13 – Illustration of an exemplary test setup with open loop**

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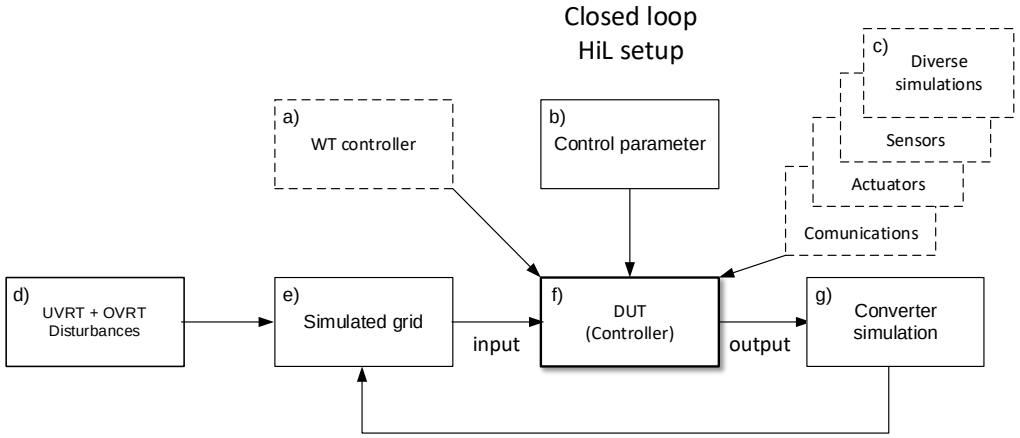

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811 **Figure 14 – Illustration of an exemplary controller-HiL test setup**

812 The table below describes the Boxes a to f/g in more detail.

813

Box	Name	Short description
a)	Wind Turbine Controller	Controls and monitor the complete WT with diverse aspects. In this case, it might be needed, to get the set up running or some features related to UVRT or/and OVRT functionalities are implemented in this controller.
b)	Control Parameter	These parameters are needed to configure each individual FRT functionality behavior at the DUT controller. During testing the test relevant parameter needs to be documented.
c)	Diverse Simulation Devices	In such a test setup, different devices, e.g. Sensors, actuators are normally not included, as they are not relevant for this functional test and the effort would be too great. However, they may need to be simulated to get the setup in operation.
d)	UVRT + OVRT Disturbances	This box symbolized the UVRT or/and OVRT voltage events, which will be seen via the simulated grid at the signal input of the DUT, e.g. low voltage measurement signal

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e)	Simulated Grid	It's the simulation of the electrical grid, which provides a grid depended feedback to the simulated converter signal output (P, Q,..).
f)	DUT (e.g. controller of the converter)	DUT which shall be the same technical setup (hardware and software), defined by the manufacturer as it will be in the e.g. complete converter
g)	Converter Simulation	If it is desired to analyze the DUT functionalities in a closed loop fashion, this box simulates the converter. This simulation translates the DUT's command signals (output) into a reaction of the converter, which feedback into the simulated grid and hence the DUT's input..

Figure 15 – Description of the different components of the test set up, illustrated in Figure 13 and Figure 14

Basically, the exact structure of the test bench depends on the planned function tests and their further use in the overall validation concept. The DUT needs to be embedded into a technical environment simulation, such that it is able to operate as in a complete WT. This can be individually different, and the setup above describes on possible version.

The following measurement values needs to record:

- Input and output of the DUT (box f)

Further measurement signals might be useful to show the functionality and needs to be defined by the manufacturer.

7.4.3.1 Requirements for controller test bench (3c)

The controller must operate with the same SW and HW as the turbines in the field to verify correct functionality. The source must replicate the grid events or grid disturbances with a sufficient accuracy to verify the response of the controller.

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7.5 Test bench equipment

To make the DUT/WT operate dynamically when installed on the test bench and perform certain electrical tests specific test bench equipment can be used. The following chapters describes the equipment typically used for performing tests and the requirements.

7.5.1 mHiL system

This section addresses the mechanical-level HiL (mHiL) system, which emulates the missing rotor and relevant auxiliary system. This section does not address power-level HiL systems, which may possibly be used for grid emulators.

Compared to the general overview for mHiL operated test benches, given in Figure 6 and Figure 8, a more detailed look in to the mHiL-setup is given in Figure 16. The statements for mHiL made in this section are valid for all types of test benches using a mHiL system.

The mHiL system comprises of two major functionalities, the “Rotor- and Structure Emulation” (short “rotor emulation”) and the “Sensor-Actuator and Interface Emulation” (short: “actuator emulation”). The rotor emulation simulates the wind field, aeroelastic, the rotor, the drive train and if needed other structural dynamics, such as tower, in real-time. In a simplified manner one can consider this a real-time wind turbine simulator. Furthermore, it controls the test bench’s prime mover, so that the wind turbine’s drive train behaves according to the rotor’s mechanical properties and the current aerodynamic conditions. Naturally, these conditions depend on signals of the wind turbine’s control system, which is interlinked with the rotor emulation via the actuator emulation.

The actuator emulation simulates the signals and dynamics of missing sensors or actuators, such as wind vane, measured bending moments, pitch or yaw actuators in real-time. If required, more signals such as status signals etc. can be emulated separately. The aim of this actuator emulation is to minimize software changes that are required on the WT’s control system.

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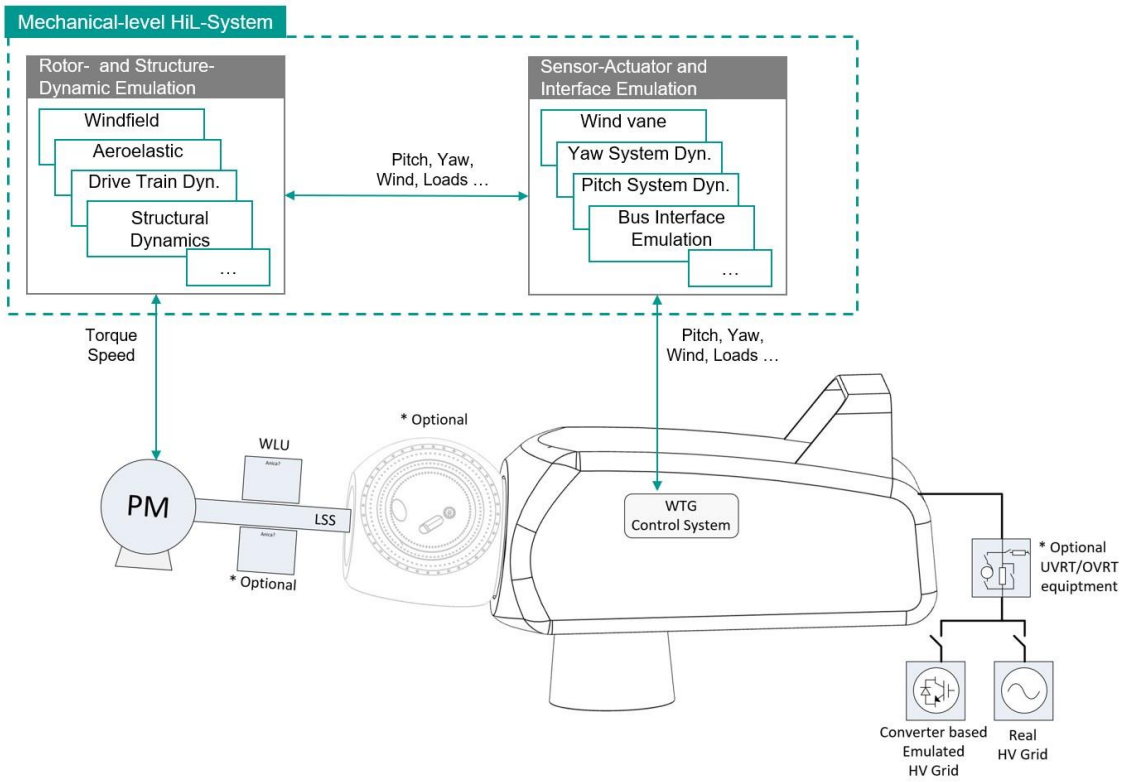

Figure 16 - General block diagram of the mechanical Hardware-in-the-Loop system required to operate nacelle or Electrical Generation System in mHiL-mode.

The forthcoming section will give some minimum requirements on the mHiL system and especially on the models used therein.

7.5.1.1 Requirements for rotor and structure dynamic emulation

The purpose of rotor and structural dynamics emulation is to reproduce the influence of the rotor on the behaviour of the WT by means of the prime mover of the test bench. In general, the rotor

- converts fluid-mechanical energy into rotational energy, depending on the inflow conditions (wind speed and direction), the pitch angle and the rotational speed and
- determines the natural frequencies of the mechanical drive train.

Accordingly, the Rotor and Structure Dynamic Emulation also has two essential tasks. It reproduces the aerodynamic properties of the rotor in real-time using a suitable method and thereby restores the dynamic behaviour of the drive train determined by the rotor inertia. The required functions within the rotor emulator and corresponding requirements are given in Table 3.

Table 3 - Functions of the rotor and structure emulation and related requirements.

Function and Description	Level 1	Level 2

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Wind field • Simulation of wind conditions (mean wind speed and turbulence intensity) • generated according to IEC 61400-1	Spatially resolved 3D wind field (turbulent)	Punctual effective mean wind speed at hub height (turbulent)
Aeroelastic • Simulation of the aerodynamic properties of the rotor, i.e. transfer of wind power into the induced prime mover torque	Detailed rotor model (model based on load calculation tools from the type certification process)	Static Cp-Grid (function of rotor speed, pitch angle, wind speed)
Drive Train Dynamics • Simulation of the coupled rotor-drive train dynamics of the original wind turbine with respect to the rotational degree of freedom on the test bench	Multi-mass oscillator (emulation of coupled rotor-drive train eigenfrequencies)	Single-mass oscillator (emulation of dynamics, i.e. inert behavior)
Structural Dynamics • Simulation of the influence of further structural dynamics (e.g. influences of the tower) on the rotational degree of freedom and their coupling	Detailed structural models (model based on load calculation tools from the type certification process)	without any further structural models

To ensure consistency in test bench testing, one level should be used throughout all tests. For the execution of individual test items on nacelle and subsystem test benches, the necessary level of detail of the rotor and structural dynamics emulation (level 1 or level 2) and the sensor-actuator emulation must be agreed in each individual case.

7.5.1.2 Requirements for sensor-actuator and interface emulation

The purpose of the sensor-actuator and interface emulation is to reproduce the signal interface and the dynamic behaviour of sensors and actuators that are not available due to installation on the test bench. How many of these interfaces are required depends on the wind turbine and the agreements of all parties involved. In principle, the smallest possible modification is desirable. In this section, only the systems affected in any case are taken into account.

Table 4 - List of system for which sensor, actuator or interfaces are emulated in order to operate WT in mHiL mode.

System and Required Emulation	Requirements
Pitch System: • Sensor and actuator Interface emulation; Signal interface to WT controller, i.e. signal conditioning and protocol	

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• Actuator emulation for dynamic behaviour; Simulation of the dynamic response of the pitch actuator (simulation at model level if the pitch actuator is not physically operated).	Inertial forces and external aerodynamic conditions Delay times of the actuators (motor, cylinder)
Yaw System (Optional) • Sensor and actuator Interface emulation Signal interface to WT controller, i.e. signal conditioning and protocol • Actuator emulation for Dynamic behaviour Simulation of the dynamic response of the Yaw actuator (simulation at model level if the pitch actuator is not physically operated)	 Inertial forces and external aerodynamic conditions Delay times of the actuators (motor, cylinder)
Wind Sensor • Sensor interface emulation Emulate Interface to provide wind information (speed, direction) from HiL-System to WT controller, i.e. signal conditioning and protocol • Sensor Emulation (Optional) Emulation of sensor disturbance by rotor and sensor's dynamic behavior	 No requirements, as of minor importance for testing
Other Sensor (e.g. blade root bending moments, nacelle acceleration, …) • Sensor interface emulation Emulate Interface to provide required information from HiL-System to WTcontroller • Sensor emulation Emulation of dynamic behaviour of sensor or measured quantity	 If a sensor has relevant dynamic behaviour, it is to consider. If the dynamic of the measured quantity is relevant and not covered by another system, such as e.g. rotor-structural dynamic emulation, it is to consider.
External References (Optional) • Interface emulation Emulate Interface to provide external references from HiL-System to WT controller, i.e. signal conditioning and protocol	 No requirements, as of minor importance for testing

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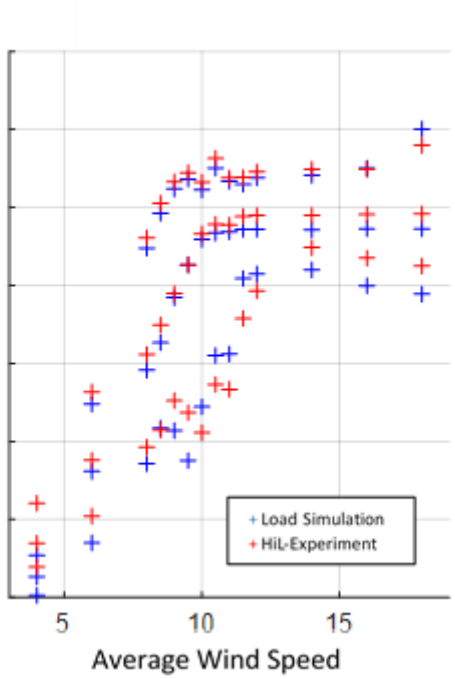
886 **7.5.1.3 Validation procedure**

887 The correct emulation of the wind turbine's mechanic and aerodynamic properties by the mHiL
888 system are crucial for the validity of the measurement results derived at test benches. The
889 emulation can be considered as reliable if the results of the real-time simulation and load
890 calculation simulation according to IEC61400-1 and IEC 61400-3 match with sufficient
891 accuracy.

892 For validation the static and dynamic properties the following procedure is proposed. It is recommended
893 to operate the wind turbine at different wind speed from cut-in to above rated wind speed in turbulent
894 (or laminar) conditions and compare the resulting power, generator speed and pitch angle to load
895 simulation results according to IEC61400-1 and IEC 61400-3. When using turbulent wind conditions, it
896 is recommended to compare mean, min and max values as illustrated in XXX. Differences below 10%
897 are acceptable for mechanic quantities. Pitch differences shall remain below 2°.

898 For verifying the dynamic performance of the mHiL system and the test bench, different tests
899 can be considered. In a first test, the DUT operates at different wind speeds from cut-in to
900 cut-out in turbulent conditions. The wind speed steps can be up to 4 m/s. For determining the
901 dynamics, the spectrum of the generator speed or power and is calculated and compared to
902 simulation results of the same test run.
903 For a type 3 wind turbine, a UVRT test can be carried out to determine the dynamics and
904 calculate the spectrum, since the voltage drop leads to a step-like excitement of the
905 mechanical drive train.

906 The difference of the resulting eigenfrequencies should not exceed 5% of its nominal value,
907 which correlates with tolerances of the mechanical models itself. Eigenfrequencies are typically
908 only considered up to 2-5 Hz for that purpose.



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910 **Figure 17 - Suggested reporting on comparison between mHiL-operated test bench and load**
911 **simulation.**

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