



BSI Standards Publication

Wind energy generation systems

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

National foreword

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TECHNICAL SPECIFICATION

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

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

WIND ENERGY GENERATION SYSTEMS –**Part 21-4: Measurement and assessment of electrical characteristics –
Wind turbine components and subsystems**

FOREWORD

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

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

Draft	Report on voting
88/1048/DTS	88/1079/RVDTS

Full information on the voting for its approval can be found in the report on voting indicated in the above table.

The language used for the development of this Technical Specification is English.

This document was drafted in accordance with ISO/IEC Directives, Part 2, and developed in accordance with ISO/IEC Directives, Part 1 and ISO/IEC Directives, IEC Supplement, available at www.iec.ch/members_experts/refdocs. The main document types developed by IEC are described in greater detail at www.iec.ch/publications.

A list of all parts in the IEC 61400 series, published under the general title *Wind energy generation systems*, can be found on the IEC website.

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

- reconfirmed,
- withdrawn, or
- revised.

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 the grid compliance. The electrical characteristics of the WPP and WTs are verified and validated 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, *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*
- IEC TR 61400-21-3, *Wind energy generation systems – Part 21-3: Measurement and assessment of electrical characteristics – Wind turbine harmonic model and its application*
- IEC TS 61400-21-4, *Wind energy generation systems – Part 21-4: Measurement and assessment of electrical characteristics – Wind turbine components and subsystems*
- IEC TS 61400-21-5, *Wind energy generation systems – Part 21-5: Configuration, functional specification, and validation of hardware-in-the-loop test bench for wind power plants¹*

Figure 1 gives an overview of the TC 88 standards, in relation to grid connection requirements, and the interaction to the power system responsible TSOs and the relevant system TCs under IEC as TC8/SC8a.

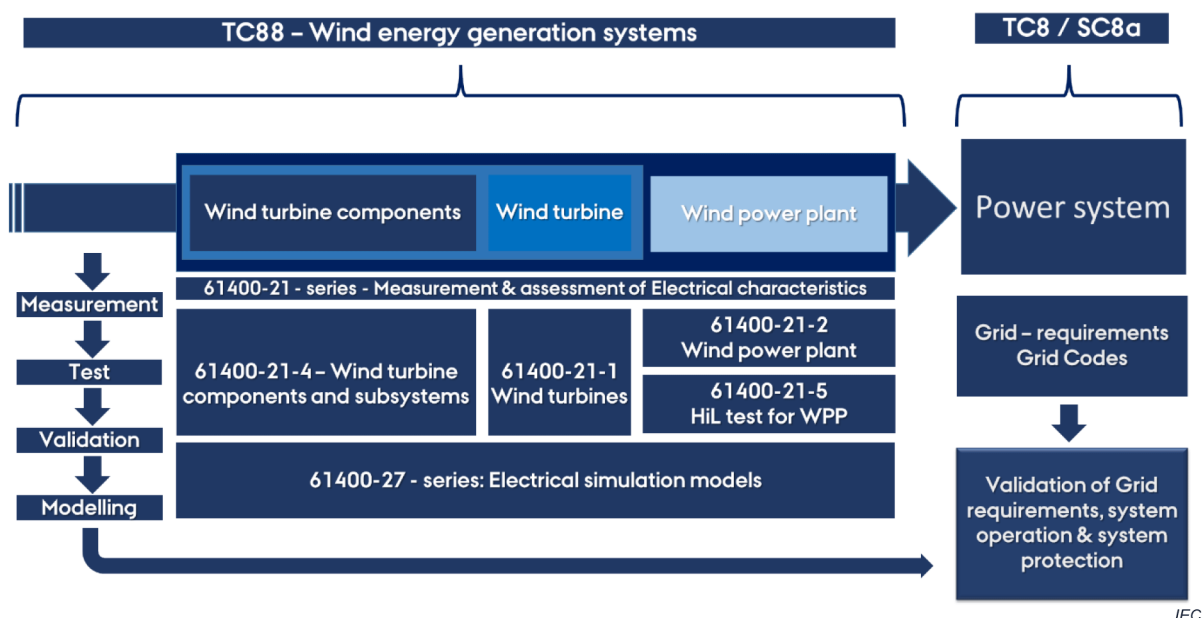


Figure 1 – Overview of TC 88 – Standards related to grid connection

¹ Under preparation. Stage at the time of publication: IEC/ACD TS 61400-21-5:2024.

This technical specification is a supplement to IEC 61400-21-1 and IEC 61400-21-2. This part of the IEC 61400-21 series specifies the test procedures and defines a uniform methodology for standardizing the measurement, testing and assessment of the electrical characteristics of wind turbine (WT) components and subsystems. This standardization serves as the basis for verifying the electrical behaviour of WTs and WT families using test bench systems. The results of these component and subsystem tests can be used to replace site specific tests as defined in IEC 61400-21-1. Only a few exceptions may still require test site measurements.

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

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

- Power quality aspects: flicker control, active filtering, impedance measurement
- Steady state operation: voltage, frequency and current unbalance capability
- Control performance: grid impedance variations and island operation
- Dynamic performance: real RoCoF and phase jump

The procedures defined in this technical specification provide the measurement data that, for example, form the basis for the validation of simulation models, as defined in the IEC 61400-27 series, as shown in Figure 1.

This document defines:

- The minimum test setup in relation to the test & measurements of the electrical characteristics in relation to grid compliance requirements.
- The system requirements for the test bench to perform these measurements.
- The procedures for the transferability of test results to wind turbine and wind turbine families
- The documentation requirements for the wind turbine component and subsystem test results

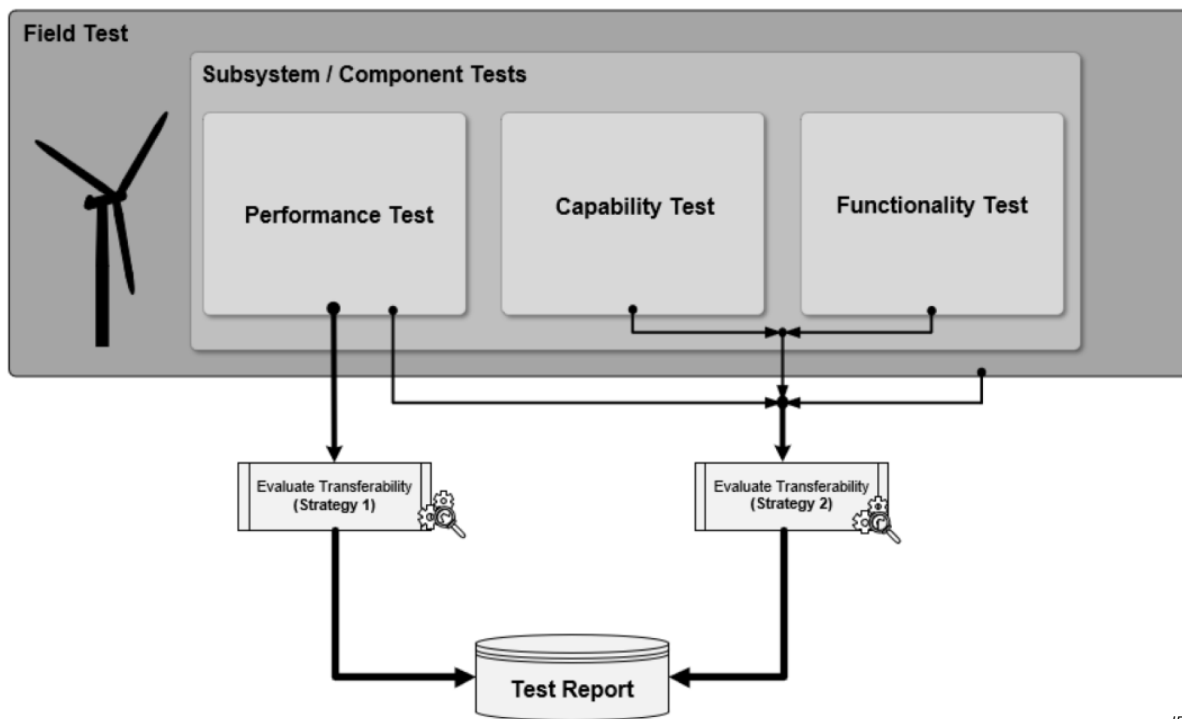
The defined test and measurement procedures can be performed as a combination of performance, capability, and functionality tests (Figure 2), which are carried out on different test benches. As shown in Figure 2, two strategies can be followed to derive measurement results:

Strategy I: Performance tests can be carried out on a suitable subsystem test bench. The measurement results are directly transferable to WT measurements.

Strategy II: Capability and functionality tests on subsystems and/or components on appropriate test benches in combination with performance tests. The combination of the measurement results are transferable to WT measurements.

NOTE 1 Performance tests include all aspects of capability and functionality tests.

NOTE 2 The strategy description above and Figure 2 describe the case when a test report with all tests is required, hence performance, capability and functionality tests are included. Naturally, if a report for single tests, e.g. grid protection, is needed, this might only require a functionality, or a capability test.



IEC

Figure 2 – Overview of performance-, capability- and functionality test, and their relation to the field tests

A detailed test overview including the minimal required setup for the verification and assessment of the electrical characteristics are defined in Annex B. An overview of the required test level is given in Clause 4.

If it has been validated and verified that the test results are not affected by the different hierarchy of test bench level, a lower hierarchy level than stated (see Figure 7) would be acceptable.

If a procedure other than those described here is agreed with the responsible stakeholders, like certification bodies, testing labs, manufacturers of the DUT, it can be used, provided that the procedure used is validated and verified.

NOTE 3 This document will be further developed with the increased experience of the defined test procedures as well as the development of test systems and simulation model validation as defined e.g. in the IEC 61400-27 series.

The structure of this document is as follows:

Clause 4: Provides an overview of the required tests and measurement procedures.

Clause 5: Defines the minimum setup and the interfaces of the DUT, used for the validation of the electrical characteristics.

Clause 6: Defines the minimum system requirements and characteristics for the test bench systems to perform tests of the requested minimal DUT configuration, as well the overall requirements for the measurement systems. The detailed requirements are defined in the specific chapters.

Clause 7: Defines the test setup and test conditions for the IEC 61400-21-1 specific tests in relation to power quality, steady state operation, dynamic response and control performance, as well as the documentation requirements and an evaluation for the transferability of the test results towards the WT.

Clause 8: Defines the additional tests, which are only possible in a controlled test bench setup as described in this document in relation to power quality, steady state operation, control performance and dynamic response, as well as the documentation requirements and an evaluation for the transferability of the test results towards the WT.

This document contains further the following informative annexes:

Annex A: Defines a report template, which can be used as basis for the reporting.

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

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

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

Annex E: Shows examples and procedures for the harmonic assessment methods.

Annex F: Examples of Fault ride-through validation procedures for the functionality & capability test.

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

Annex H: Overview and definition of voltage fault types.

Annex I: Summary of grid emulator requirements

Annex J: Grid adaptability test using grid emulator

WIND ENERGY GENERATION SYSTEMS –

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

1 Scope

This part of IEC 61400, which is a Technical Specification, specifies a uniform methodology, defining measurement, testing and assessment procedures of electrical characteristics of wind turbine components and subsystems, as basis for the verification of the electrical capabilities of wind turbines and wind turbine families.

This document includes the following aspects:

- definitions of test bench, subsystems and interface;
- definitions of system requirements for the test bench to perform relevant measurements (grid strengths, short circuit power, THD, ...);
- measurement procedures for quantifying the electrical characteristics;
- test and measurement procedures for verifying and validating the electrical characteristics of components and subsystems in relation to grid compliance requirements;
- procedures for the transferability of the component and subsystem test results, measured at the test bench, to WT product families;
- documentation requirements and validation procedures of components, subsystems and wind turbines.

The results of the measurements and assessments of the wind turbine components and subsystems will be used as input for the verification of electrical capabilities as described in IEC 61400-21-1 and for the validation and verification of the electrical simulation models for wind power plants (WPP) as described in 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 the IEC 61400-27 series;
- Power Plant control 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 (switchgears, cables, transformer, generator etc.), which are covered by other IEC standards;
- mechanical, structural loads and lifetime test;
- noise and acoustical measurements;
- certification procedures and grid compliance at wind power plant level;
- communication system functional and performance tests as defined in e.g. the IEC 61400-25 series.

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

- Low voltage (LV) refers to $100 \text{ V} < U_n \leq 1 \text{ kV}$;
- Medium voltage (MV) refers to $1 \text{ kV} < U_n \leq 35 \text{ kV}$;
- High voltage (HV) refers to $35 \text{ kV} < U_n \leq 230 \text{ kV}$;
- Extra high voltage (EHV) refers to $U_n > 230 \text{ kV}$.

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 60255-127, *Measuring relays and protection equipment – Part 127: Functional requirements for over/under voltage protection*

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

IEC TR 61000-3-6:2008, *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 61400-1, *Wind energy generation systems – Part 1: Design requirements*

IEC 61400-3-1, *Wind energy generation systems – Part 3-1: Design requirements for fixed offshore wind turbines*

IEC 61400-3-2, *Wind energy generation systems – Part 3-2: Design requirements for floating offshore wind turbines*

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*

IEC TR 61400-21-3:2019, *Wind energy generation systems – Part 21-3: Measurement and assessment of electrical characteristics – Wind turbine harmonic model and its application*

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

IEC 61557-12, *Electrical safety in low voltage distribution systems up to 1 000 V AC and 1 500 V DC – Equipment for testing, measuring or monitoring of protective measures – Part 12: Power metering and monitoring devices (PMD)*

IEC 62586-2, *Power quality measurement in power supply systems – Part 2: Functional tests and uncertainty requirements*

ISO/IEC GUIDE 98-3, *Uncertainty of measurement – Part 3: Guide to the expression of uncertainty in measurement (GUM:1995)*

3 Terms, definitions, symbols, units and abbreviated terms

For the purposes of this document, the following terms, definitions, symbols, units and abbreviated terms 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 Terms and definitions

3.1.1

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, 3.1.1, modified: EUT replaced with DUT]

3.1.2

capability

steady state and dynamic behaviour of the component or system in relation to the defined parameters

Note 1 to entry: Capability is more about the breadth and depth of functionalities a system can provide, while performance is often measured with specific metrics related to efficiency and response time. E.g. reactive power capability describes the specified steady state capability of the reactive power production or consumption.

3.1.3

capability test

test used to assess whether a component or system is able to meet the specifications or requirements against defined parameters

Note 1 to entry: Used to demonstrate what the DUT is capable of. The end of the test is usually determined by the DUT and often not predetermined. Because during capability testing often the absolute limits of the DUT are reached, in many cases it is not possible to see a control loop working but only the effect of limiters or timers are to be observed.

3.1.4

closed-loop control

type of automatic control in which control actions are based on feedback signals from the controlled equipment or system

[SOURCE: IEC 62270:2013, 2.10, modified – only first sentence of definition used]

3.1.5

compliance test

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

[SOURCE: IEC 60050:192:2015, 192-09-02]

3.1.6

component

smallest unit where all necessary functions are available in the unit and which cannot be divided into smaller parts without losing the primary function

Note 1 to entry: Examples for wind turbine components are: generators, transformers, switchgear, gearboxes, converters.

3.1.7**component test**

test on a single component, whose necessary functions and required behaviour are not dependent on other components or systems

Note 1 to entry: A test done on component level may be valid for all turbine variants where the same component is applied. (e.g. the protection device, if this is an independent unit).

3.1.8**power coefficient** **C_p**

ratio of the net electric power output of a wind turbine to the power available in the free stream wind over the rotor swept area

3.1.9**emulation**

combination of a real-time simulation (e.g. rotor simulation, grid simulation) and an actuator element, where the actuator element itself exhibits relevant dynamics (e.g. motor, converter)

3.1.10**emulator**

device consisting of real-time simulation and actuator element

Note 1 to entry: Examples for emulators in this TS are: grid emulator, comprising real-time grid simulation and power converter, or rotor and structure emulator, comprising of a real-time wind turbine simulation and a motor.

3.1.11**flicker step factor**

normalized measure of the flicker emission due to a single switching operation of the PGU:

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

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;

$P_{\text{st, fic}}$ is the short-term flicker severity from the PGU on the fictitious grid;

S_n is the nominal apparent power of the PGU;

$S_{k, \text{fic}}$ is the short-circuit apparent power of the fictitious grid

Note 1 to entry: The short-term flicker severity $P_{\text{st, fic}}$ is calculated over the time period T_p .

3.1.12**functionality**

ability to achieve a specified operation performed by a component or subsystem or a software program

Note 1 to entry: The activity of performing a function normally employs a system of displays, controls and instrumentation

3.1.13**functionality test**

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

Note 1 to entry: Functionality tests are typically done without any power production as e.g. the grid protection test and the functionality test only address that the correct steady state is reached, dynamic performance like: rise time, settling time, overshoot, etc. are not addressed.

3.1.14**fault ride-through****FRT**

ability of a wind turbine or wind power plant to stay connected during faults in the grid

Note 1 to entry: The term Fault Ride Through is a general definition for grid faults, in this TS we are using the term FRT only for the undervoltage and overvoltage grid fault types and the ability to stay connected during the UVRT and OVRT events.

3.1.15**grid emulator**

programmable power supply, capable of emulating various grid conditions to facilitate the testing of grid-connected equipment

Note 1 to entry: Sometimes also referred as grid simulator. See also definition "emulator".

3.1.16**higher frequency component**

component applied for voltages and currents which is measured and grouped in accordance with Equation B.1 of IEC 61000-4-7:2002/AMD1:2008

3.1.17**Hardware-in-the-Loop****HiL**

simulation method that allows a hardware under test to interact in a closed-loop with a real-time simulation model, which represents missing components

Note 1 to entry: See Annex G for explanations on different variants of HiL.

3.1.18**mechanical-level Hardware-in-the-Loop****mHiL**

HiL where the real-time simulation model interfaces with the hardware under test on the mechanical level.

Note 1 to entry: See Annex G for explanations on different variants of HiL.

3.1.19**nacelle**

housing which contains the drive-train and other elements on top of a horizontal axis wind turbine tower

[SOURCE: IEC 60050-415:1999, 415-01-07]

3.1.20**natural impedance**

impedance of the physically existing, passive components of a grid emulator, e.g. transformer, filter, etc.

3.1.21**negative sequence component of the fundamental**

for a three-phase system with phases L_1 , L_2 and L_3 , the symmetrical sinusoidal three-phase set of voltages or currents having negative frequency, the absolute value of which is equal to the fundamental frequency

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

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

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

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

3.1.22**no-load test**

performance validation of the test equipment, with an open electrical connection to the DUT

Note 1 to entry: The test can be done with the main transformer, if this has no impact on the test equipment setup and results. The setup should be stated in the test report.

3.1.23**nominal apparent power**

apparent power of the wind turbine while operating at nominal current and nominal voltage and frequency:

$$S_n = \sqrt{3} U_n I_n \quad (3)$$

Wind tat $Q = 0$

where

U_n is the nominal voltage;

I_n is the nominal current

3.1.24**nominal current**

nominal value I_n of wind turbine current, which is calculated from nominal active power P_n and

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

3.1.25**nominal active power**

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

3.1.26**overshoot**

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

Note 1 to entry: See Figure 3.

3.1.27

open-loop

form of control without feedback

[SOURCE: IEC 62270:2013, 2.36]

3.1.28

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.

3.1.29

performance

steady state and dynamic fulfilment according to the specification of the component or system in relation to defined parameters

3.1.30

performance test

measurements and tests carried out to determine the ability of the DUT against selected parameters to achieve an intended behaviour

Note 1 to entry: Performance is often measured with specific metrics related to efficiency and response time, while capability is more about the breadth and depth of functionalities a system can provide.

Note 2 to entry: Used to demonstrate how the DUT will perform under well-defined conditions. The desired performance is usually declared by the manufacturer or defined by a standard.

3.1.31

phase jump

rapid change in the phase angles of the supply voltage

3.1.32

phase shift

- a) the absolute magnitude of the difference between two phase angles
- b) the displacement in time of one periodic-waveform relative to other waveforms

[SOURCE: ISO/IEC 14776-121:2010, 3.1.69]

3.1.33

Power Hardware-in-the-Loop

PHIL

HiL where the real-time simulation model interfaces with the hardware under test on electrical (power) level

Note 1 to entry: See Annex G for explanations on different variants of HiL

3.1.34

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

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

$$\underline{X}_1 = \frac{1}{3} (\underline{X}_{L1} + \underline{a} \underline{X}_{L2} + \underline{a}^2 \underline{X}_{L3}) \quad (4)$$

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 2 to entry: In a balanced harmonic-free system, only the positive sequence component of the fundamental exists. For example, if phase voltage phasors are symmetrical $\underline{U}_{L1} = Ue^{j\theta}$, $\underline{U}_{L2} = Ue^{j(\theta+4\pi/3)}$ and $\underline{U}_{L3} = Ue^{j(\theta+2\pi/3)}$ 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 2 to entry has been added.]

3.1.35

Q-capability

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

3.1.36

ramp-down time

time during which the measured value decreases from 90 % to 10 % of the target value

3.1.37

reaction time

time from the start of the event until the observed value reaches 10 % of the step change

Note 1 to entry: See Figure 3.

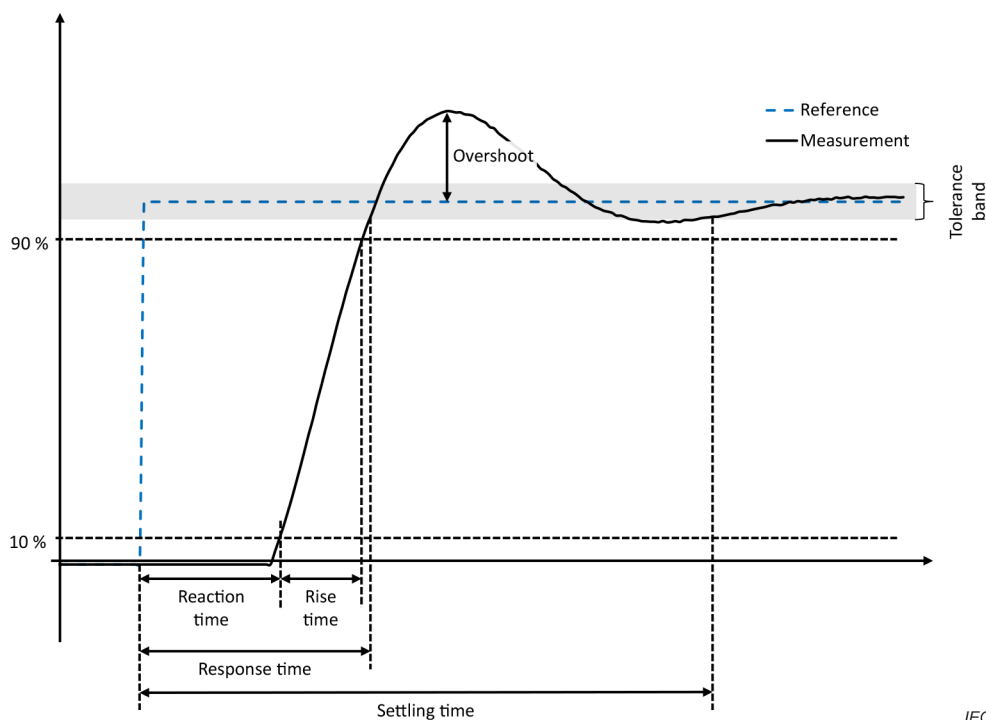


Figure 3 – Example of step response

3.1.38

recovery time

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

3.1.39

response time

elapsed time from the start of event until the observed value enters for the first time the defined tolerance band

Note 1 to entry: See Figure 3.

3.1.40**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.

3.1.41**settling time**

elapsed time from start of event until the observed value continuously stays within the defined tolerance band

Note 1 to entry: See Figure 3.

3.1.42**short-circuit apparent power**

product of the current in the short-circuit at a point of a system and a conventional voltage, generally the operating voltage

Note 1 to entry: 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.

[SOURCE: IEC 601-01-14:1985, 601-01-14, modified – Note 1 to entry added.]

3.1.43**short-circuit impedance**

equivalent impedance at the fault location

Note 1 to entry: The calculation of the short-circuit impedance is generally based on the rated data of the electrical equipment and the topology of the grid.

3.1.44**short-circuit ratio****SCR**

ratio of the short-circuit apparent power S_k to the nominal apparent power S_n :

$$SCR = \frac{S_k}{S_n} \quad (5)$$

3.1.45**simulation**

use of a similar or equivalent system to imitate a real system, so that it behaves like or appears to be the real system

Note 1 to entry: Simulation serves the purpose of analysing the behaviour of a system, For performing simulations, a model is needed together with actualized sets of data and a platform able to execute the simulation.

[SOURCE: ISO 16781:2021, 3.1.9, modified – Note 1 to entry added]

3.1.46**source**

electric power supply to feed signals or energy into an electrical system or a controller

3.1.47**start of event**

instant of time where the stimulus value deviates outside its defined stimulus tolerance band for the first time

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

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

3.1.48

static error

deviation between the obtained values compared to a requested reference value

3.1.49

steady state

status of the system obtained when the settling time has expired

3.1.50

sub-group

grouping method according to IEC 61000-4-7:2002/AMD1:2008

Note 1 to entry: Sub-grouping is used for integer sub-grouped harmonic currents and voltages and for interharmonic centered sub-group currents and voltages.

3.1.51

sub-group total harmonic current distortion

THC

ratio of the RMS value of the harmonic sub-groups (I_h) to the RMS value of the sub-group associated with the nominal current (I_n):

$$THC = \sqrt{\sum_{h=2}^{50} \left(\frac{I_h}{I_n} \right)^2} \quad (6)$$

3.1.52

sub-group total harmonic voltage distortion

THDS_{U_h}

ratio of the RMS value of the harmonic sub-groups (U_h) to the RMS value of the sub-group associated with the nominal voltage (U_n):

$$THDS_{U_h} = \sqrt{\sum_{h=2}^{h_{\max}} \left(\frac{U_h}{U_n} \right)^2} \quad (7)$$

Note 1 to entry: In this document the value of $h_{\max}$ is either 50 or 180 as given in the specific requirements.

3.1.53

subsystem

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

3.1.54

subsystem test

test on a subsystem, where all necessary functions and performance for the test are available in the subsystem and are not dependent on other components or systems

Note 1 to entry: Test done on a subsystem is valid for all turbine variants where the subsystem is used.

3.1.55

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 $\pm 10\%$ of the nominal value if nothing else is stated.

Note 3 to entry: See Figure 3.

3.1.56

validation

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

Note 1 to entry: In relation to this document, the defined test and measurement procedures are validation procedures as the validation is based on experimental data in relation to an intended use.

Note 2 to entry: In this document the defined tests procedures etc. are validation tests, as this document does not verify that specific requirements are met.

[SOURCE: IEC 60050-192:2015, 192-01-18, modified – notes to entry modified]

3.1.57

verification

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

Note 1 to entry: In relation to this document 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.

Note 2 to entry: In relation to this document the verification is as well used in relation to the test bench systems e.g. within the process to verify the turbine real-time models as defined in 6.7.2.5.

3.1.58

virtual impedance

impedance seen by the DUT at the POC when the grid emulator adjusts the voltage at the POC according to the equivalent circuit shown in Figure 4 thereby compensating for the natural impedance of the grid emulator

Note 1 to entry: The implementation can for example be done as follows: The grid emulator calculates its output voltage (U_{POC}) based on the virtual impedance parameter ($Z_{virtual}$) and the injected current (I_{DUT}) of the DUT.

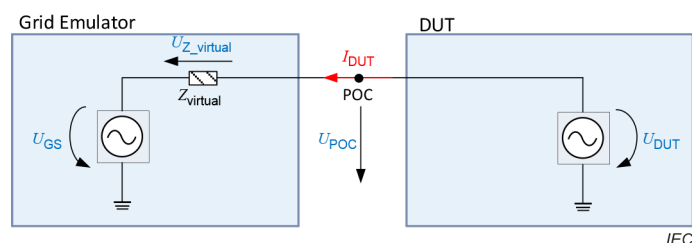


Figure 4 – Simulated equivalent circuit of the grid emulator and the DUT

The following equation applies to the voltage at the POC: $U_{POC} = U_{GS} + I_{DUT} * Z_{virtual}$.

Note 2 to entry: As this is a control feature, the bandwidth of the virtual impedance is limited to the grid emulator's control bandwidth. Beyond this bandwidth, the grid emulator's natural impedance is dominant.

3.1.59

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.

3.1.60

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

3.1.61

unbalance factor

in a three-phase system, the degree of unbalance expressed by the ratio $|\underline{X}_2/\underline{X}_1|$ (in percent) between the values of the negative sequence component X_2 and the positive sequence component X_1 of voltage or current

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

3.1.62

undervoltage 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.

3.1.63

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:

$$\underline{X}_0 = \frac{1}{3}(\underline{X}_{L1} + \underline{X}_{L2} + \underline{X}_{L3}) \quad (8)$$

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

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

3.2 Symbols, units and abbreviated terms

In this document, the following symbols and units are used.

ψ_k	network impedance phase angle (°)
$\alpha_m(t)$	electrical angle of the fundamental of the measured voltage (°)
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_i	frequency injection
$f_{\text{inertia, recovery}}$	frequency threshold where the turbine shall stop boosting active power (Hz)
$f_{\text{inertia, trigger}}$	frequency threshold where the turbine shall start boosting active power (Hz)
h	harmonic order

$i_m(t)$	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)
$THDS_{U,h}$	sub-group total harmonic voltage distortion up to the h^{th} harmonic order
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_{UVRC}	the difference between U_n of the WT and U_{min} in p.u. (undervoltage range capability)
U_{OVRC}	the difference between U_{max} and U_n of the WT in p.u. (overvoltage range capability)
U_{pre}	pre-fault voltage (V)
UUF	voltage unbalance factor

Aux	Auxiliary equipment
cap.	capacitor
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
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
p.u.	per unit

RMS	root mean square
RoCoF	rate of change of frequency
RoCoV	Rate of change of voltage
SW	Software
TB	Test bench
THC	total harmonic current distortion
THD	Total Harmonic Distortion
UVRT	Undervoltage ride-through
V_R	voltage of emulated grid
WLU	Wind Load Unit
WT	Wind Turbine

4 Overview of tests

Table 1 gives an overview of the required test levels for the different tests and measurements as described in this document, as well as the recommended requirements for the test system, where the DUT is connected to as defined in Clause 6.

Table 1 – Overview of tests according to Clause 7

Clause / Subclause	Test case	Test bench type by DUT		Type of test (C, P, F) ^a
Power quality aspects		WT Type I-III	WT Type IV	
7.2.1	Flicker	Field test		C
7.2.2	Flicker and voltage change during switching operations	Field test		C
7.2.3	Harmonics	2b		C
Steady state				
7.3.2	Observation of active power against wind speed	Field test		C
7.3.3	Maximum power	2a		P
7.3.4	Reactive power characteristic (Q=0)	2a	3a	P
7.3.5	Reactive power capability	2b	3b	C
7.3.6	Voltage dependency of PQ diagram	2b	3b	C
7.3.7	Unbalance factor	2b	3b	P
Control performance				
7.4.1	Active power control	2a	2a	P
7.4.2	Active power ramp rate limitation	2a		P
		4a		F
7.4.3	Frequency control	2a		P
		4a		F
7.4.4	Synthetic inertia	2a		P
7.4.5	Reactive power control	2b	3b	P
		4a		F
Dynamic performance				

Clause / Subclause	Test case	Test bench type by DUT		Type of test (C, P, F) ^a
7.5.2	Voltage fault ride-through – Testing according to Strategy 1	2a	3a	P
7.5.3	Voltage fault ride-through – Testing according to Strategy 2	2a	3a	C
		4a	4a	F
Grid protection				
7.6.2	Grid protection	3b		C
		4b		F
7.6.3	Rate of change of frequency RoCoF (df/dt)	3b		C
		4b		F
7.6.4	Reconnection time	1a		C
^a P: Performance test; C: Capability test; F: Functional test				

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

Table 2 – Overview of tests according to Clause 8

Clause / Subclause	Test case	Test bench type by DUT		Type of test (C, P, F) ^a
Power quality aspects		WT Type I-III	WT Type IV	
8.2.1	Flicker control	2a	3a	P
8.2.2	Flicker and voltage change during switching operations	2a		P,F
8.2.3	Active filter / Sink for harmonics	2b	3b	P,F
8.2.4	Impedance measurements	2b	3b	P
Steady state				
8.3.1	Voltage capability	2b	3b	C
8.3.2	Frequency capability	2b	3b	C
8.3.3	Current Unbalance Factor in an unbalanced system	2b	3b	C
Control performance				
8.4.1	Grid Impedance variations	2a	3a	C
8.4.2	Island operation	1a		C
Dynamic performance				
8.5.1	RoCoF – real df/dt – capability	2b	3b	C
		4a		F
8.5.2	Phase jump	2b	3b	C
		4a		F
^a P: Performance test; C: Capability test; F: Functional test				

If it has been validated and verified that the test results are not affected by the different hierarchy of test bench level, a lower hierarchy than stated would be acceptable. A detailed description of the test bench levels is given in Annex B.

Different settings and parameter variations can be performed as a functionality test, on a test bench type 4a or 4b as defined in 6.6, to validate the ability against e.g. site or country specific requirements.

Tests to verify separately the capability of the auxiliary equipment can be performed on a test bench category 5a or 5b as defined in 6.6.

The required test bench system always refers to the minimum required system. If a higher hierarchy test bench system level is used the other levels are automatically included.

Tests can also be performed at WT level, following the same procedures as defined in this document and described in Annex J.

Regarding the hierarchy of the test benches see 6.1 and especially Figure 7.

5 Definitions of minimum DUT, components and subsystems

5.1 General

This clause 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.

5.2 Description of components and subsystems

Figure 5 gives an overview of the main components, subsystems and control functions as well as the main input and output parameters, which influence the different test and measurement procedures as described in this document. The overview represents the different WT concepts and not the real placement in the WT. The structure follows the modular structure as defined in IEC 61400-27-1.

As an example: For the reactive power capability measurement the subsystems i.e. power conversion system and electrical connection (including the WT type specific components) are influencing the reactive power capability measurements and should be represented in the DUT. The responsible control system "grid power control" should be included as well.

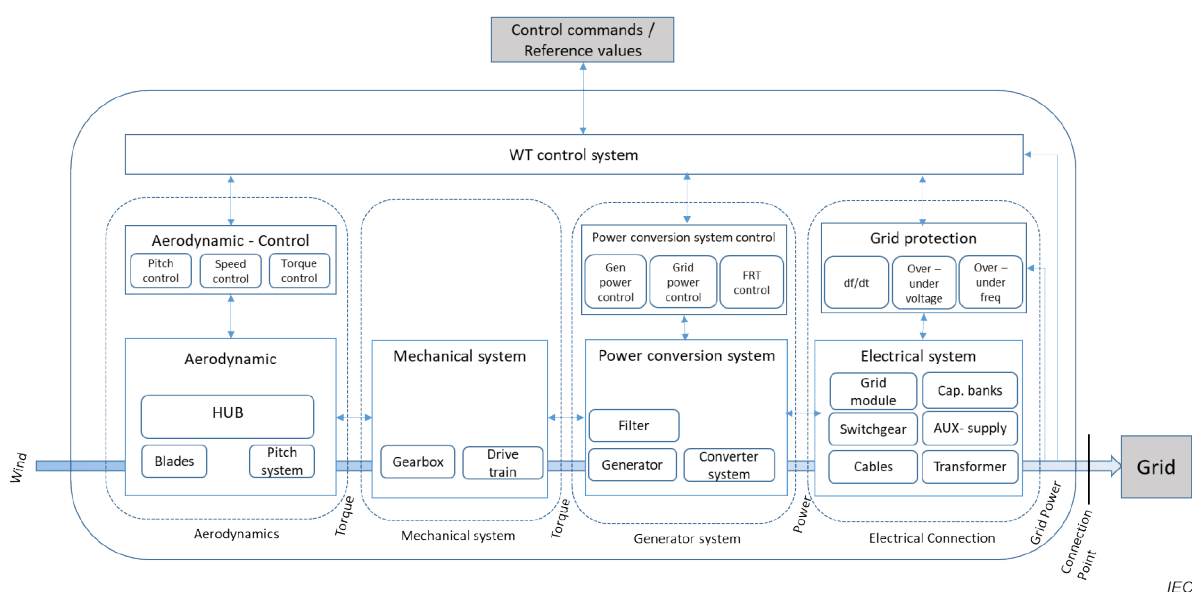


Figure 5 – Generic structure of WT types

Depending on the WT type some of the following main components as defined in Table 3 will be part of the different subsystems for the different WT types I, II, III and IV as defined in IEC 61400-27-1.

Table 3 – Overview of subsystems and main functions

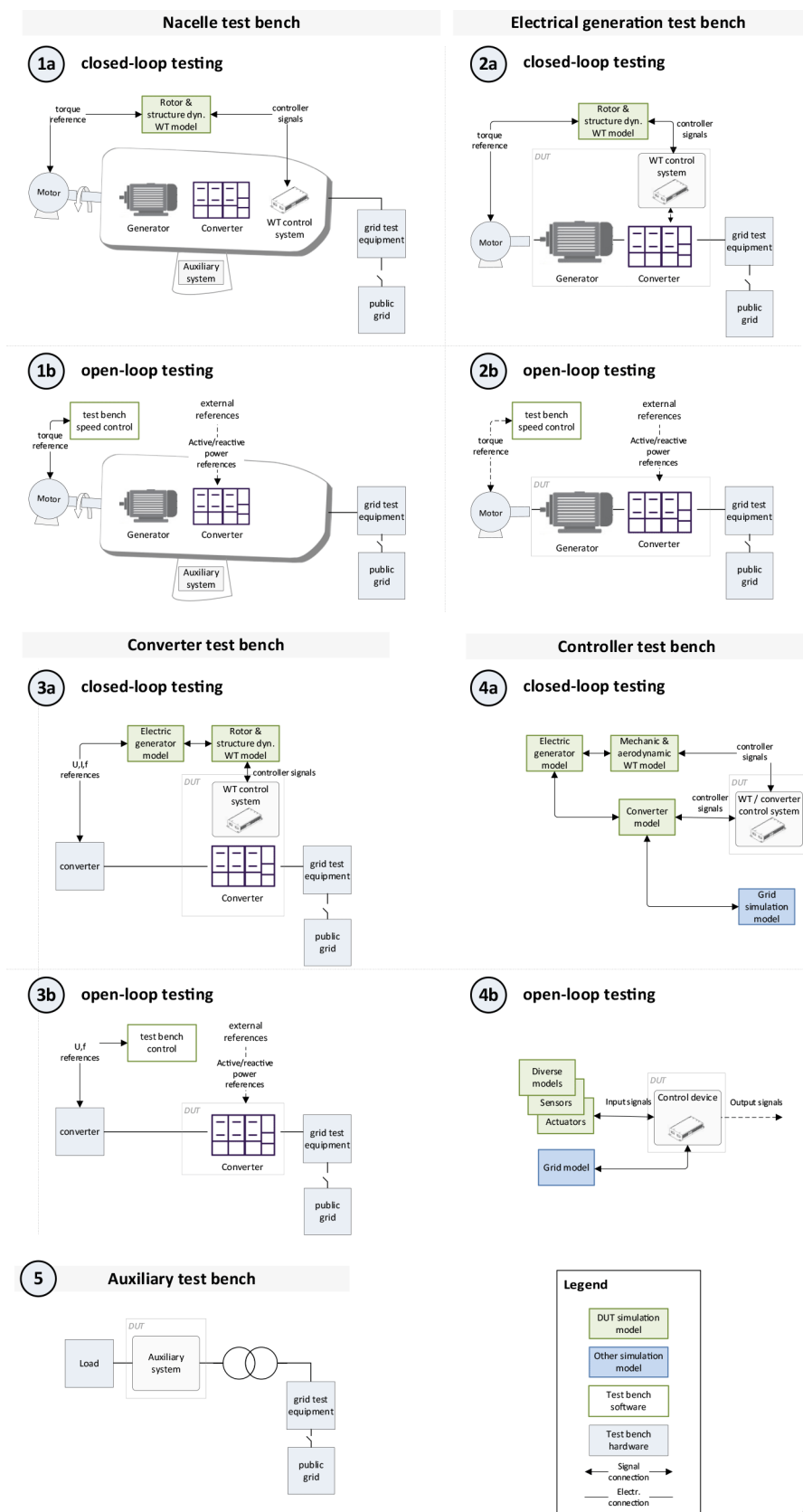
Subsystem	Main Components	Description
Aerodynamics	Blades	Blades of the WT
	Pitch system	Mechanical / electrical system to rotate the blades around their longitudinal axis
	Hub	fixture for attaching the blades assembly to the rotor shaft
	Control functions	
	Pitch control	Control system to control the 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 on the main shaft
Subsystem	Main Components	Description
Mechanical System	Gearbox	Set of gears and there casing to change the speed
	Drive system	Mechanical drive train – main shaft bearings etc.
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 as defined in IEC 61400-27-1
	Filter	Filter system for harmonic distortion reduction, e.g. harmonics caused by switching frequency
	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
Subsystem	Main Components	Description
Electrical connection	Transformer	LV to MV transformer
	Cables	Tower cables etc.
	Switchgear	Protection device including all required breakers, contactors, etc.
	Aux supply	Supply of the auxiliary equipment in the WT
	Grid module	Grid measurement module
	Cap. banks	Reactive power compensation to compensate for the reactive power demand from the generator system e.g. for Type I and Type II
	Grid Protection functions	
	Frequency protection	Over- and under frequency protection
	Voltage protection	Over- and undervoltage protection
	df/dt	Protection against fast frequency changes e.g. RoCoF

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

6 Test bench systems

6.1 General

To test the electrical characteristics of wind turbines, test benches of different system levels and different complexities can be used. Figure 6 gives a general overview of the different test bench types included in this document. As shown in Figure 6, test bench types are numbered from 1 to 5. At nacelle test benches (1), electrical generation test benches (2), converter test benches (3) and controller test benches (4) the DUT can be tested in two different ways, which is reflected in the subtypes (a) and (b). Type (a) test benches enable a closed-loop operation of the DUT with its WT control system. This requires that the test bench is supplemented by real-time simulations of the WT, which are used inside a Hardware-in-the-Loop systems controlling the test bench. The logic is that with each next test bench type 1a, 2a, 3a and 4a, the number of simulated WT components increases.



IEC

Figure 6 – General overview of test bench systems included in this TS, including the logical distinction between closed-loop and open-loop testing of wind turbines

NOTE 1 The term "grid test equipment" used in Figure 6 summarizes all sorts of test equipment, which can be introduced to create certain grid states and events, e.g. grid emulators, UVRT hardware equipment etc. (see 6.7.4).

The test benches 1b, 2b, 3b and 4b do not allow a closed-loop operation of the WT control system. Instead, the DUT is operated open-loop, not including the WT control system.

NOTE 2 The terms closed-loop and open-loop testing of wind turbine are referring to the WT main control system, i.e. converter related controls are operating in closed-loop in any case. Furthermore, the test bench itself, e.g. the PM, will be in closed-loop control, e.g. speed control, independent of the test bench type (a) or (b).

The test bench type 5 refers to auxiliary test benches. Compared to types 1 to 4 the complexity of the tested system is reduced significantly and no subtypes a or b are considered.

The hierarchy of the test benches is illustrated in Figure 7. It shows that all tests, which require a type (b) test bench, can also be executed on the corresponding type (a) test bench. It also shows that tests can be executed on test bench types with a lower number (1*, 2*, 3*) than required. Type (a) test benches can only be replaced by type (a) test benches of lower number.

NOTE 3 For example, a test which requires test bench type 2b can be executed on 2a, 1b or 1a test bench, but it cannot be executed on a test bench type 3a or 3b.

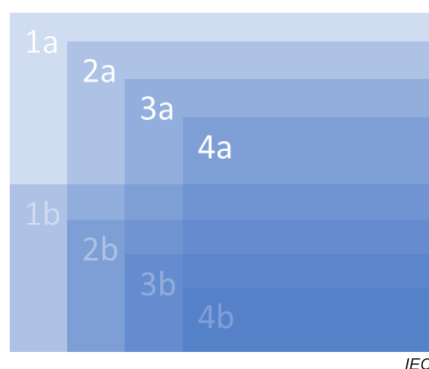


Figure 7 – Hierarchy of the different test bench types

The following subclauses describe the different test bench types, the general test bench equipment and related requirements.

6.2 Nacelle test benches

6.2.1 General

At nacelle test benches the complete nacelle is installed at the test bench and the different components of the WT (e.g. generator, gearbox, hydraulics, main bearing(s) and electrical cabinets) are mounted in the nacelle in their original positions and structures.

If parts of the electrical systems are located in or outside the tower section of the WT, they can be placed next to the test bench.

If no other test of the electrical auxiliary system exists, the components, which affect the tested electrical characteristics, shall be installed and operating.

The nacelle test benches are distinguished as:

- type 1a: "Nacelle test benches – closed-loop testing", cf. Figure 8
- type 1b: "Nacelle test benches – open-loop testing", cf. Figure 9

6.2.2 Nacelle test benches – closed-loop testing (1a)

6.2.2.1 General

At nacelle test benches for closed-loop testing, the WT's main control system and subsidiary control systems are active during testing. The response to the electrical tests are representative for real site operation, since the mHiL system ensures correct dynamic response of the WT and its power, torque and speed control systems. As described in more detail in 6.7.2, this is done by emulating the aerodynamic and mechanical properties of the rotor, the tower and missing actuators.

An example test setup for a nacelle test bench is shown in Figure 8.

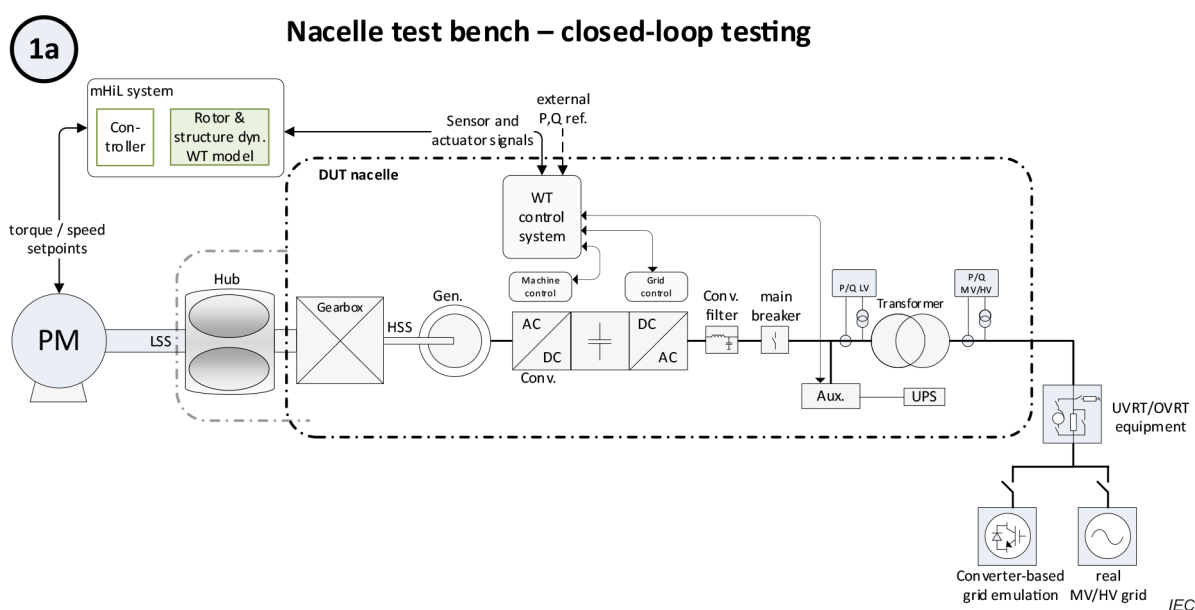


Figure 8 – Example of a nacelle test bench and a Type IV WT setup for closed-loop testing

NOTE The DUT and the test bench setup in the figure above are examples. They do not allow general conclusions to be drawn as to whether, e.g., switchgear, auxiliary equipment, transformers or hubs are part of the setup.

Furthermore, all electrical systems that influence the grid event have to be present and operational as well.

The mHiL system itself is described in more detail in 6.7.2.

The prime mover (PM) is described in 6.7.3.

The UVRT/OVRT equipment is described in 6.7.4.

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 6.7.5.

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

6.2.2.2 Requirements for nacelle test benches (1a)

The DUT is operated with its original control software with minimum changes. Changes shall be documented. In order to achieve results equivalent to site tests, the mHiL operation shall be verified. 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 according to 6.7.2.5.

6.2.3 Nacelle test benches – open-loop testing (1b)

6.2.3.1 General

At nacelle test benches for open-loop testing, the WT's main control system is typically not operational during testing. However, the relevant subsidiary control systems, such as converter related controls, are active during testing.

This test bench type can be used if the test does not require a correct dynamic speed response of the DUT or if the DUT only needs to operate according to its characteristic power/speed curve. For this purpose, the prime mover of the test bench can be operated in speed control mode, as illustrated in Figure 9.

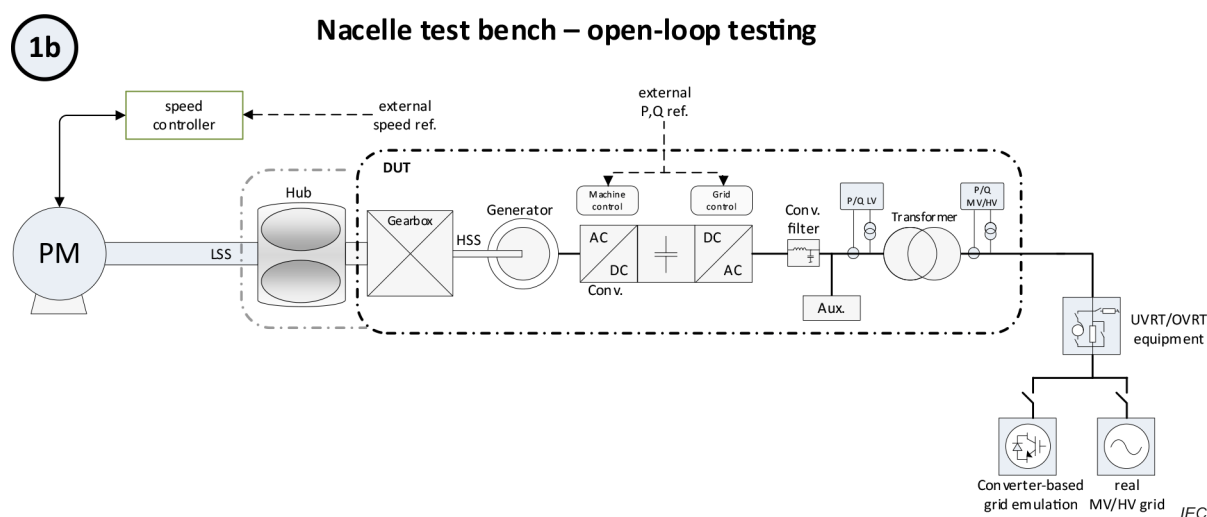


Figure 9 – Example of a nacelle test bench and a type IV WT setup for open-loop testing

NOTE The DUT and the test bench setup in the figure above are examples. They do not allow general conclusions to be drawn as to whether, e.g., switchgear, auxiliary equipment, transformers or hubs are part of the setup.

The test setup is controlled with a speed controller, which sends references to the prime mover. From an external source active and reactive power references are sent to the DUT grid side converter. With that, specific operating points in terms of speed, active and reactive power can be configured and tested.

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 6.7.5.

Typically, the WT controller and the auxiliary systems are not active in this test bench configuration during testing. Because of the missing WT control and mHiL system, the dynamic response is not representative of real on-site operation.

6.2.3.2 Requirements for nacelle test benches (1b)

The test bench's speed controller shall be able to set the desired references with sufficient accuracy, to allow execution of the planned tests. Accuracy shall be documented.

6.3 Electrical generation test benches (2a and 2b)

6.3.1 General

At an electrical generation test bench the WT's electrical drive train including e.g. generator and converter, is the DUT. The mechanical components of the drive train, such as gearbox, main bearing, or any corresponding auxiliaries are not included in this test setup.

Electrical generation test benches are distinguished as

- type 2a: "Electrical generation test bench – closed-loop testing", cf. Figure 10
- type 2b: "Electrical generation test bench – open-loop testing", cf. Figure 11

6.3.2 Electrical generation test benches – closed-loop testing (2a)

6.3.2.1 General

At electrical generation test benches for closed-loop testing, the WT's main control system and the converter control system are active during testing together. As shown in Figure 10, the WT control system operates the WT and is connected with the mHiL system to ensure realistic closed-loop operation of the WT.

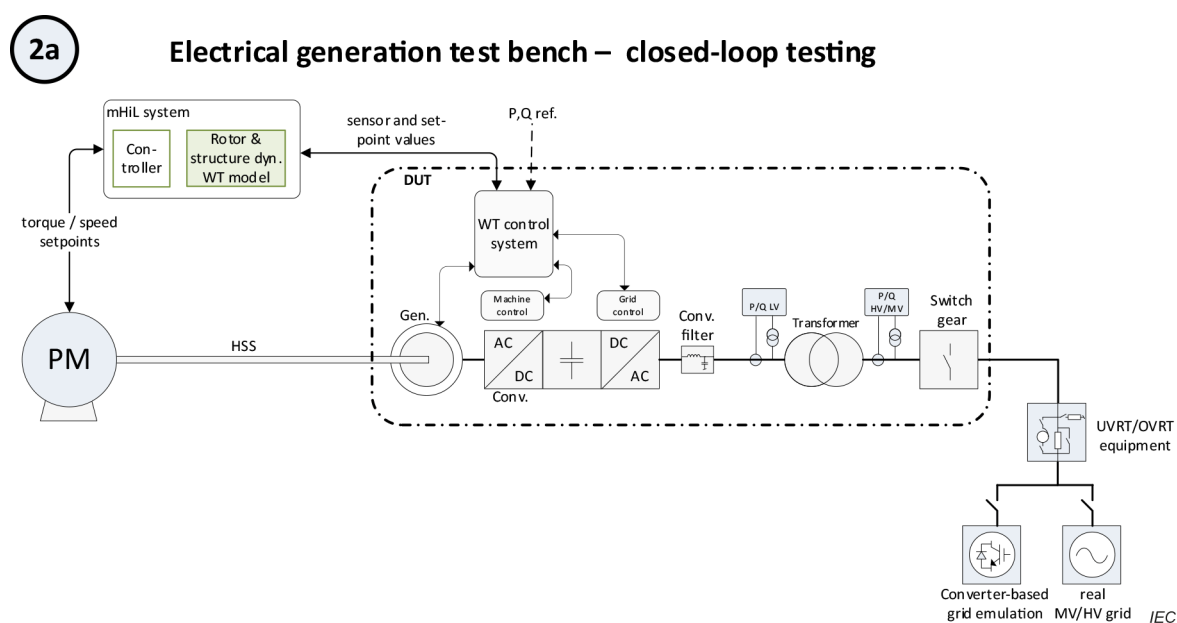


Figure 10 – Example of an electrical generation test bench and a Type IV WT setup for closed-loop testing

NOTE The DUT and the test bench setup in the figure above are examples. They do not allow general conclusions to be drawn as to whether, e.g., switchgear, auxiliary equipment, transformers or hubs are part of the setup.

For closed-loop testing (Figure 10), the DUT at the electrical generation test bench is operated with its original control software along with the mHiL system. The mHiL system emulates the dynamic speed response of the wind turbine at the test bench. With that, the DUT on the test bench has the same dynamic speed response as the corresponding wind turbine in the field.

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 6.7.5.

The mHiL system itself is described in more detail in 6.7.2. Compared to the mHiL system used for nacelle test benches, it features an additional simulation model to emulate the impact of the missing mechanical drive train components.

6.3.2.2 Requirements for electrical generation test benches (2a)

The DUT is operated with its original control software with minimum changes. Changes shall be documented. The mHiL system shall be verified against proven simulation models or field data according to 6.7.2.5. The test bench's control system shall be capable of applying mechanical loads as dynamically as required by the mHiL system.

6.3.3 Electrical generation test benches – open-loop testing (2b)

6.3.3.1 General

If the test bench does not have an mHiL system and the DUT does not have the complete WT control system, then the tests can be conducted with the test bench in speed control, following speed references. As for the nacelle test bench in speed control (6.2.3) the test setup is controlled by a speed controller as illustrated in Figure 11. The references for speed of the PM, active and reactive power references for the WT converter, are provided from external.

As the WT control is not operating, the dynamic speed response is not representative of real on-site operation.

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 6.7.5.

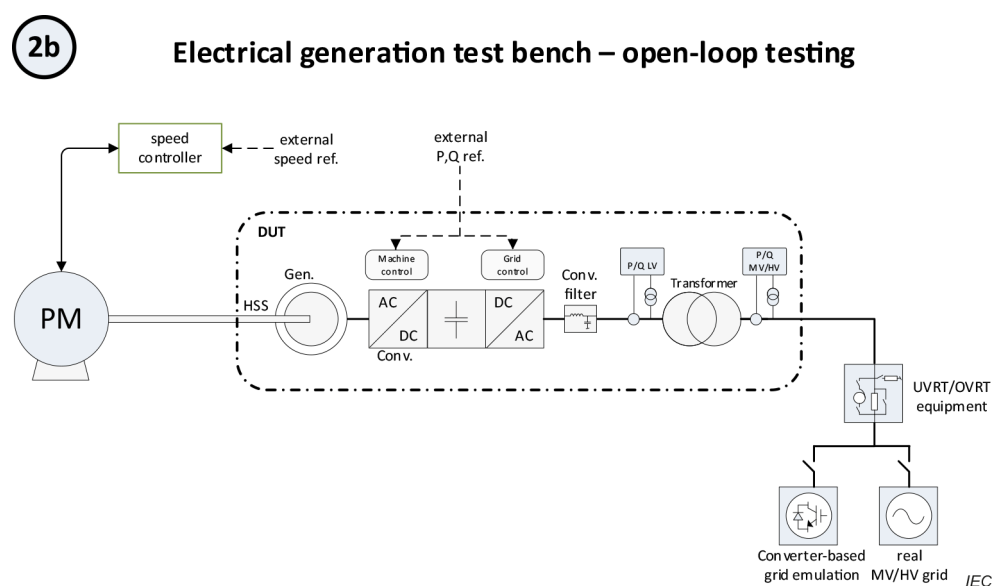


Figure 11 – Example of an electrical generation test bench and a Type IV WT setup for open-loop testing

NOTE The DUT and the test bench setup in the figure above are examples. They do not allow general conclusions to be drawn as to whether, e.g., switchgear, auxiliary equipment, transformers or hubs are part of the setup.

6.3.3.2 Requirements for electrical generation test benches (2b)

The test bench's speed controller shall be able to set desired references to allow execution of planned tests. Accuracy shall be documented.

6.4 Converter test benches (3a and 3b)

6.4.1 General

At a converter test bench, the DUT consists of the converter system with its complete control system. The tested converter system and its filter may be installed together with additional components, e.g. chopper system or transformer, depending on the turbine architecture. The mechanical system and auxiliary systems are not part of the DUT at a converter test bench.

Especially with Type IV wind turbines, the electrical characteristics are largely determined by the converter system. Compared to nacelle test benches and electrical generation test benches, less components are installed at the test bench and conversely more components are simulated.

The converter test benches are distinguished as:

- type 3a "Converter test bench – closed-loop testing", cf. Figure 12
- type 3b "Converter test bench – open-loop testing", cf. Figure 13

6.4.2 Converter test benches – closed-loop testing (3a)

6.4.2.1 General

At converter test benches for closed-loop testing, the wind turbine control system is operational along with the converter and its control system. A realistic response of the overall control system and the converter is ensured by a Power Hardware-in-the-Loop (PHiL) system, which emulates the dynamic behaviour of the missing components, such as rotor, generator, and drive train in real time.

As described in more detail in 6.7.2, this is done by emulating the aerodynamic and mechanical properties of the rotor, the tower and any missing actuators as well as the generator.

An example of such a test setup can be seen in Figure 12.

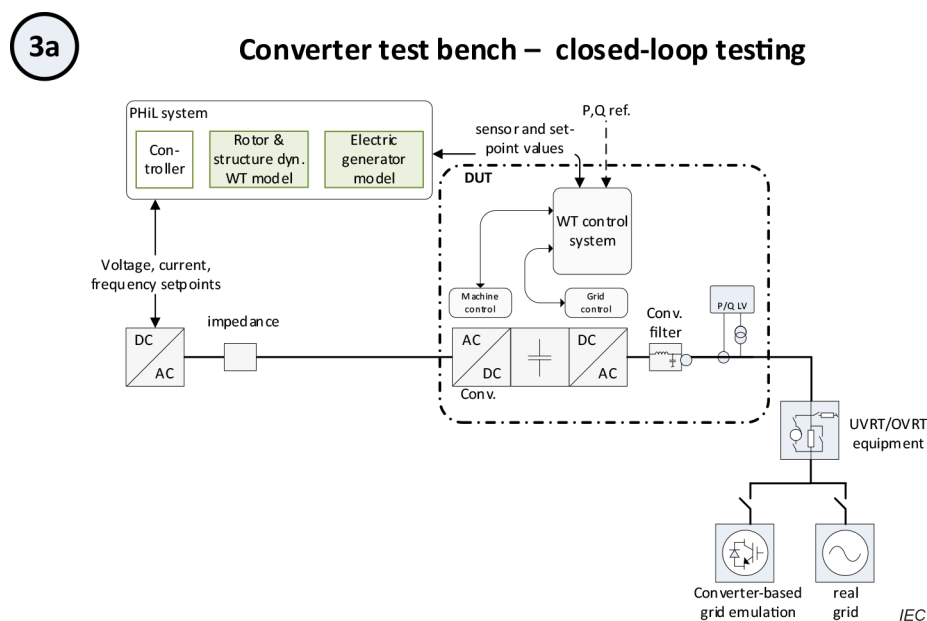


Figure 12 – Example of a converter test bench and a Type IV WT setup for closed-loop testing

NOTE 1 The DUT and the test bench setup in the figure above are examples. They do not allow general conclusions to be drawn as to whether, e.g., switchgear, auxiliary equipment, transformers or hubs are part of the setup.

The converter system is connected to a grid emulator or UVRT/OVRT equipment or directly to the public grid. A test bench converter loads the machine-side converter to ensure power flow through the DUT. This test bench converter electrically acts as the generator in the wind turbine and emulates the generator voltage behaviour (amplitude, phase angle and frequency).

For closed-loop testing of the DUT at the converter test bench, the WT control system is connected to a PHiL system, which itself controls the test bench converter. Among others, the PHiL system contains the same simulation models as the mHiL system for type 1a or 2a test benches, simulating all properties of the rotor and the drive train (extended by generator inertia) as well as any missing sensors and actuators. Beyond that, the PHiL system contains a simulation model of the WT generator's electrical properties. By combining these simulation models, the PHiL system can emulate the WT's dynamic response by means of the test bench converter.

NOTE 2 The HiL system for converter test benches is denoted as PHiL system, not because of the different simulation models inside the HiL system, but due to the electrical power interface to the DUT, instead of the mechanical interface to the DUT, as for nacelle and electrical generation test benches. See also Annex G.

6.4.2.2 Requirements for converter test benches (3a)

The DUT is operated with its original control software with minimum changes. Changes shall be documented. The PHiL-System shall be verified against proven simulation models or field data according to 6.7.2.5. The test bench's control system shall be capable of applying electrical loads as dynamically as required by the PHiL system. Accuracy shall be documented.

6.4.3 Converter test benches – open-loop testing (3b)

6.4.3.1 General

At converter test benches for open-loop testing, the overall WT control system is typically not active. The relevant converter related controls are still operational. This test bench can be used for isolated converter-system tests, when the actions of the WT controller does have very limited impact on the results.

As shown in Figure 13, the test bench converter is operated in current or voltage control and connected via an impedance with the DUT's converter system. External references are given to the test bench converter to set current or voltage profiles, respectively.

The DUT consists of the converter system with its controllers in original configuration. Thereby, the tested converter system and its filter may be installed together with additional components, e.g. chopper system or transformer, depending on the turbine architecture.

3b

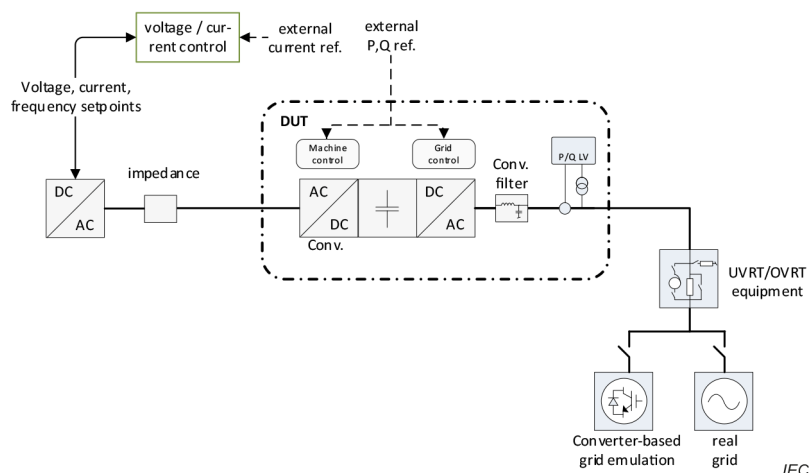
Converter test bench – open-loop testing

Figure 13 – Example of a converter test bench and a Type IV WT setup for open-loop testing

NOTE The DUT and the test bench setup in the figure above are examples. They do not allow general conclusions to be drawn as to whether, e.g., switchgear, auxiliary equipment, transformers or hubs are part of the setup.

6.4.3.2 Requirements for converter test benches (3b)

The test bench converter's current or voltage controller shall be able to set desired references with sufficient accuracy, to allow executing planned tests. Accuracy shall be documented.

6.5 Controller test benches (4a) and (4b)

6.5.1 General

At controller test benches the DUT can consist of the WT control system, the converter control system, grid protection devices or other controllers, depending on the test purpose. For this, the original control software, which is subject to test, is operated on the original controller hardware. This means that the real combination of software and hardware represent the DUT.

The controller test bench provides input and feedback signals to the WT's control system by means of simulations models (Figure 14) or external reference signals (Figure 15).

NOTE "Original software" means that it is not sufficient to test parts of the software, e.g. specific functions, in an isolated manner, but it shall be integrated in the overall software.

Control systems implemented in WT, which are considered as DUT in this chapter, are highly individual to the product. Hence, the exact structure of the test bench depends on the WT, the planned tests and their use in the overall validation concept. For this reason, the descriptions in the following can only be considered generic and may differ from implementation to implementation.

Controller test benches are distinguished as:

- type 4a "Controller test bench – closed-loop testing", cf. Figure 14
- type 4b "Controller test bench – open-loop testing", cf. Figure 15

6.5.2 Controller test benches – closed-loop testing (4a)

6.5.2.1 General

At controller test benches for closed-loop operation, the DUT consists of the WT main control system and the subsidiary converter controls. As this is a typical controller HiL test bench, only the controller hardware is physically present, while all components, e.g. converter, generator, drive train etc. are reproduced by an HiL system. This provides all necessary feedback signals to the DUT with representative dynamics.

The software of the WT's control systems is original and complete, running on its original hardware platforms. This means that in case of a distributed control system, the distributed control units shall be included. I/O signals are fed from the HiL system as shown in Figure 14, while setpoints and commands are sent from the WT control system. The HiL system contains simulation models of the rotor & structural dynamics, i.e. the mechanical part of the WT, the generator, the converter as well as relevant sensors, actuators and communications e.g. to safety. Beyond the models, which reflect the WT, the test bench contains a grid model to create desired grid states and faults. These models interact with the WT simulation model and provide feedback signals (e.g. voltage, frequency, etc.) to the WT's control system.

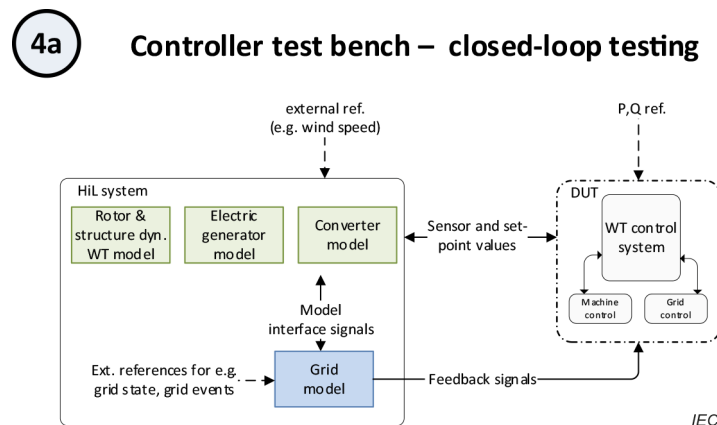


Figure 14 – Example of a controller test bench for closed-loop testing

6.5.2.2 Requirements for controller test benches (4a)

All controllers shall operate with the same SW and HW as the WT in the field to verify correct functionality. Any change shall be documented.

Requirements for the simulation models of such setup vary significantly depending on the purpose of the test setup.

The simulated grid shall replicate the grid events or grid disturbances to verify the controller response.

6.5.3 Controller test benches – open-loop testing (4b)

6.5.3.1 General

At controller test benches for open-loop testing, the WT's control systems are tested without the systems feedback on the controller output (feedforward). For this the controller feedback signals can be set as external reference. These references can be set manually or still (partly) by simulations.

The purpose is to verify the controller reactions to certain events or signals. This test bench does not allow conclusions to be drawn about the interaction of the control system with other subsystems nor about the overall WT.

Depending on the test, the DUT may be comprised of the WT controller in combination with the subsidiary converter controller or only comprised of the converter controller. As shown in Figure 15, the input signals, required to operate the WT controller are provided external reference without feedback loops, i.e. the WT controller actions do not influence these signals, as it is open-loop. The relevant WT controller output can be recorded for later analysis.

NOTE A typical example for the application of such a test bench is testing ramp-rate settings of the controller as functionality or even simpler a test of the protection system.

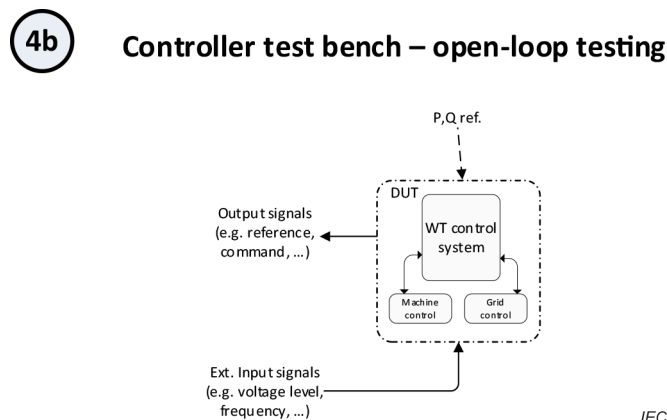


Figure 15 – Illustration of a controller test bench for open-loop testing

6.5.3.2 Requirements for controller test benches (4b)

The controller shall operate with the same SW and HW as the WT in the field to verify correct functionality, therefore all required input signals need to be provided correctly.

6.6 Auxiliary test benches (5)

6.6.1 General

For testing the auxiliary system(s) of a WT, they can be connected to an electrical source, which replicates the desired grid state or event. Thereby, when meaningful, the auxiliary system can be split into subsystems instead of testing completely.

If the auxiliary system is designed in a way that the individual auxiliary devices are decoupled from the grid side, testing up to the decoupling device may be sufficient. Figure 16 illustrates the two different principle options. The loading of the auxiliary equipment and the voltage quality at the output of the decoupling device shall be documented.

NOTE A typical decoupling device could be a UPS.

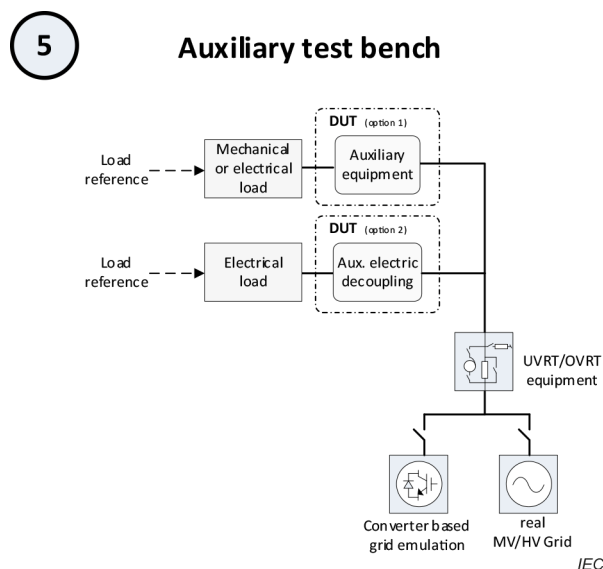


Figure 16 – Example of auxiliary test bench

This type of test bench is typically used for testing of individual components and subsystems.

Example for option 1: Testing a yaw motor directly connected to the grid, without UPS or similar, shall be mechanically loaded.

Example for option 2: Testing a yaw motor connected to the grid via full-converter or UPS, only requires to test up to the converter / UPS and electrically load it.

6.6.2 Requirements for auxiliary test benches (5)

To achieve valid results, the auxiliary equipment and the auxiliary electric decoupling, respectively, shall be loaded. The load shall be documented.

If the auxiliary equipment is tested (e.g. fans, pumps, lubrications systems, etc.), it shall operate with respect to the right environmental conditions (e.g. pressure, temperature, vibration levels).

6.7 Test bench equipment

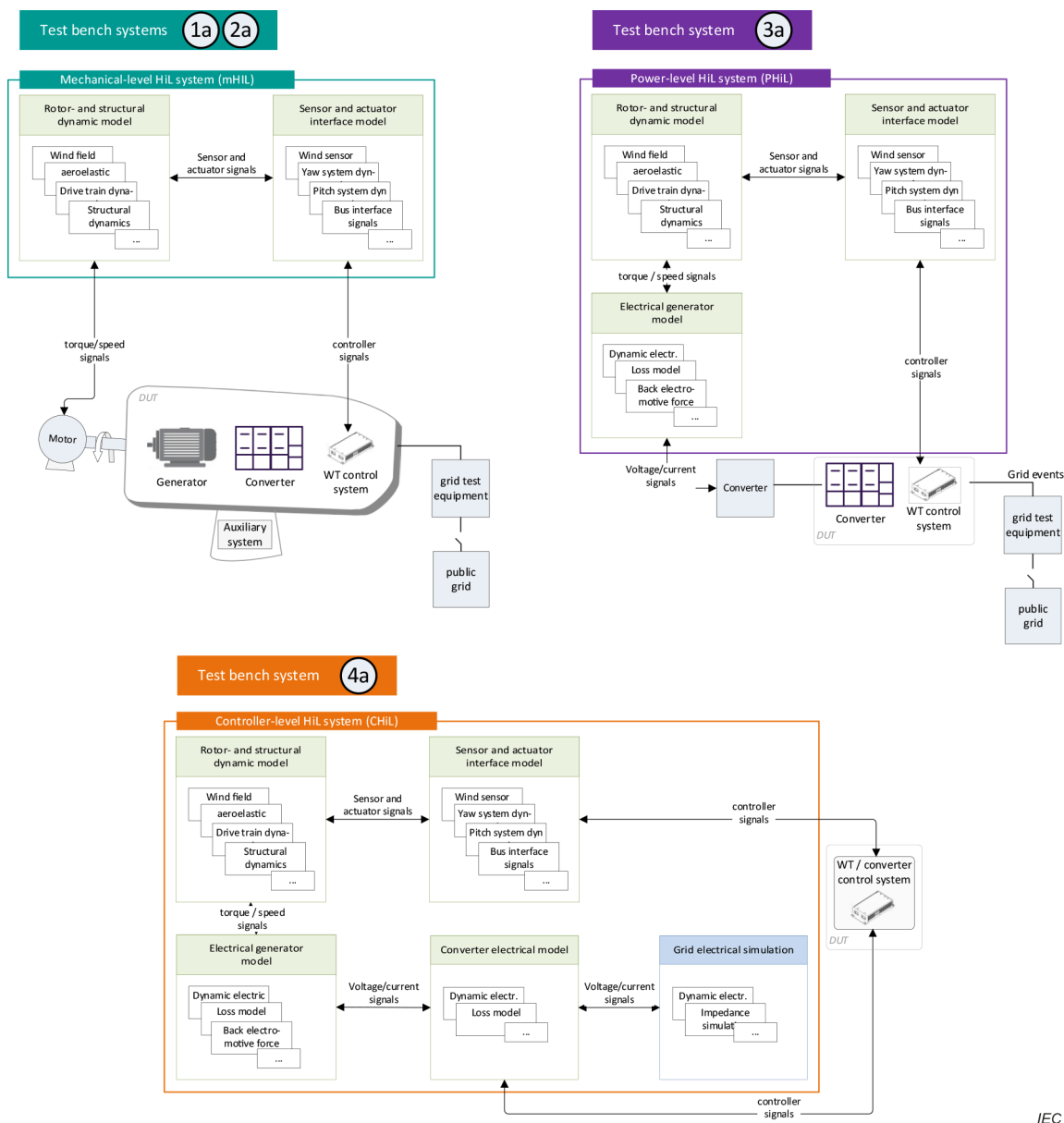
6.7.1 General

To make the DUT operate dynamically when installed on the test bench and to perform certain electrical tests, specific test bench equipment can be used. The following subclauses describe the equipment typically used for performing tests and their requirements.

6.7.2 HiL systems

6.7.2.1 General

The test bench types 1a (6.2.2), 2a (6.3.2), 3a (6.4.2) and 4a (6.5.2) require Hardware-in-the-Loop (HiL) systems, in order to operate the DUT properly at the test bench. Such HiL systems consist of models, which simulate missing parts of the tested WT in real time (e.g. rotor), and a dedicated actuator (e.g. test bench motor), which links this real-time simulation with the DUT. By this combination, the HiL system is able to emulate the behaviour of the missing WT parts.



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Figure 17 – Block diagrams of the HiL systems for different test bench types

In general, the HiL systems have to reproduce the conversion of the wind energy to mechanical and electrical energy, respectively, with the correct system dynamics and emulate missing sensor and actuator signals. Figure 17 gives an overview of the scope and structure of the HiL systems used for the different test bench types. As shown, the number of models inside the HiL systems increases from test bench type 1a to 4a, which counteracts the DUT complexity reduction. Thereby, new models are added to the HiL system, while the existing models remain.

Another property that distinguishes the HiL systems for the various test benches is the way in which they interface with the DUT. All HiL system variants interface the DUT on signal level. For type 4a test benches this is the only interface. This is also known as "Controller HiL". Beyond this signal interface, the HiL systems for type 1a and 2a test benches interface the DUT mechanically by using a motor. At type 3a test benches, the HiL system interfaces the DUT electrically by using a converter.

The control of these actuators is part of the mHiL and PHiL system. It is not addressed separately in this document, since their performance is inherently tested by the verification procedures described in 6.7.2.5.