88/889/CD

COMMITTEE DRAFT (CD)

PROJECT NUMBER: **IEC TS 61400-21-4 ED1**	
DATE OF CIRCULATION: **2022-05-27**	CLOSING DATE FOR COMMENTS: **2022-08-19**
SUPERSEDES DOCUMENTS: **88/685/NP, 88/702/RVN**	

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

This document is still under study and subject to change. It should not be used for reference purposes.

Recipients of this document are invited to submit, with their comments, notification of any relevant patent rights of which they are aware and to provide supporting documentation.

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

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?

CONTENTS

INTERNATIONAL ELECTROTECHNICAL COMMISSION

____

WIND ENERGY GENERATION SYSTEMS

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

FOREWORD

1) The International Electrotechnical Commission (IEC) is a worldwide organization for standardization comprising all national electrotechnical committees (IEC National Committees). The object of IEC is to promote international co-operation on all questions concerning standardization in the electrical and electronic fields. To this end and in addition to other activities, IEC publishes International Standards, Technical Specifications, Technical Reports, Publicly Available Specifications (PAS) and Guides (hereafter referred to as "IEC Publication(s)"). Their preparation is entrusted to technical committees; any IEC National Committee interested in the subject dealt with may participate in this preparatory work. International, governmental and non-governmental organizations liaising with the IEC also participate in this preparation. IEC collaborates closely with the International Organization for Standardization (ISO) in accordance with conditions determined by agreement between the two organizations.
2) The formal decisions or agreements of IEC on technical matters express, as nearly as possible, an international consensus of opinion on the relevant subjects since each technical committee has representation from all interested IEC National Committees.
3) IEC Publications have the form of recommendations for international use and are accepted by IEC National Committees in that sense. While all reasonable efforts are made to ensure that the technical content of IEC Publications is accurate, IEC cannot be held responsible for the way in which they are used or for any misinterpretation by any end user.
4) In order to promote international uniformity, IEC National Committees undertake to apply IEC Publications transparently to the maximum extent possible in their national and regional publications. Any divergence between any IEC Publication and the corresponding national or regional publication shall be clearly indicated in the latter.
5) IEC itself does not provide any attestation of conformity. Independent certification bodies provide conformity assessment services and, in some areas, access to IEC marks of conformity. IEC is not responsible for any services carried out by independent certification bodies.
6) All users should ensure that they have the latest edition of this publication.
7) No liability shall attach to IEC or its directors, employees, servants or agents including individual experts and members of its technical committees and IEC National Committees for any personal injury, property damage or other damage of any nature whatsoever, whether direct or indirect, or for costs (including legal fees) and expenses arising out of the publication, use of, or reliance upon, this IEC Publication or any other IEC Publications.
8) Attention is drawn to the Normative references cited in this publication. Use of the referenced publications is indispensable for the correct application of this publication.
9) Attention is drawn to the possibility that some of the elements of this IEC Publication may be the subject of patent rights. IEC shall not be held responsible for identifying any or all such patent rights.

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.

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..   THIS TEXT IS INCLUDED FOR THE INFORMATION OF THE NATIONAL COMMITTEES AND WILL BE DELETED AT THE PUBLICATION STAGE.

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.

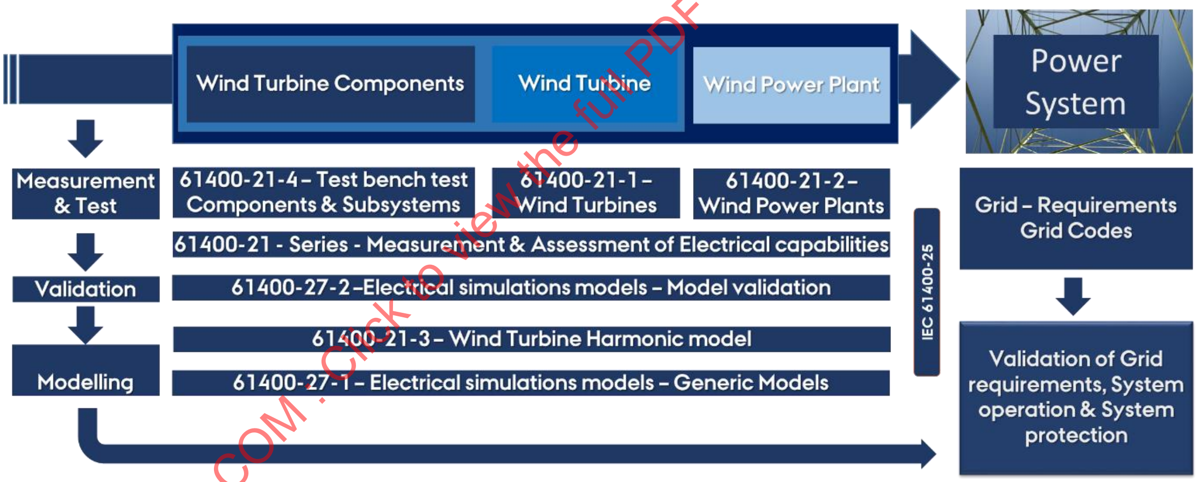


Figure 1 - Overview of TC 88 – Standards related to grid connection

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.

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.

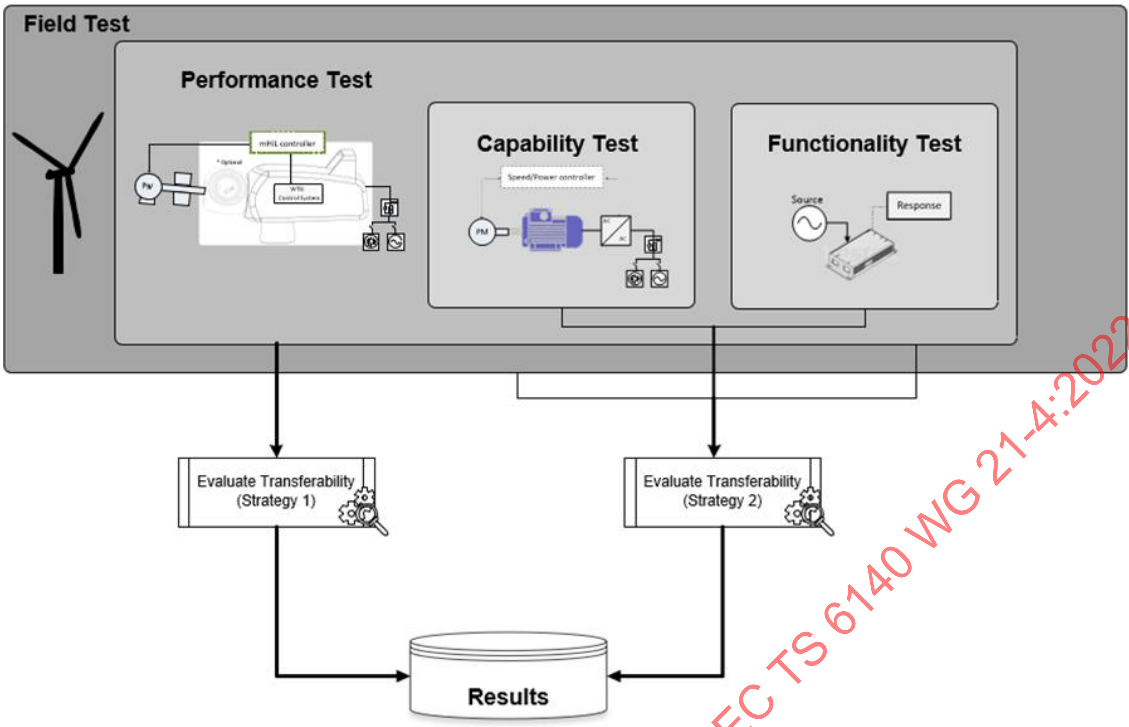


Figure 2 - Overview of functional-, capability-, and performance tests, and there relation to the field tests.

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, 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.

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

NOTE

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

Low voltage (LV) refers to 100 V < U_n ≤ 1 kV;

Medium voltage (MV) refers to 1 kV < U_n ≤ 35 kV;

High voltage (HV) refers to 35 kV < U_n ≤ 230 kV;

Extra high voltage (EHV) refers to U_n > 230 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 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*

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,

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

$c(\psi_k)$	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

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

3.18
Mechanical-level Hardware-in-the-Loop
mHiL
HiL where the real-time simulation model interfaces the hardware under test on mechanical level.

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

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

[Source: IEV 415-01-07]

3.20
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:

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

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 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 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 $U_2 = (Ue^{j\theta} + e^{j4\pi/3}\, Ue^{j(\theta+4\pi/3)} + e^{j2\pi/3}\, Ue^{j(\theta+2\pi/3)})/3 = Ue^{j\theta}\,(1 + e^{j2\pi/3} + e^{j4\pi/3})/3 = 0$

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

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

Note 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 needs to be stated in the test report

3.22
nominal apparent power
apparent power from the wind turbine while operating at nominal current and nominal voltage and frequency:

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

where

U_n is the nominal voltage;

I_n is the nominal current

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

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

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

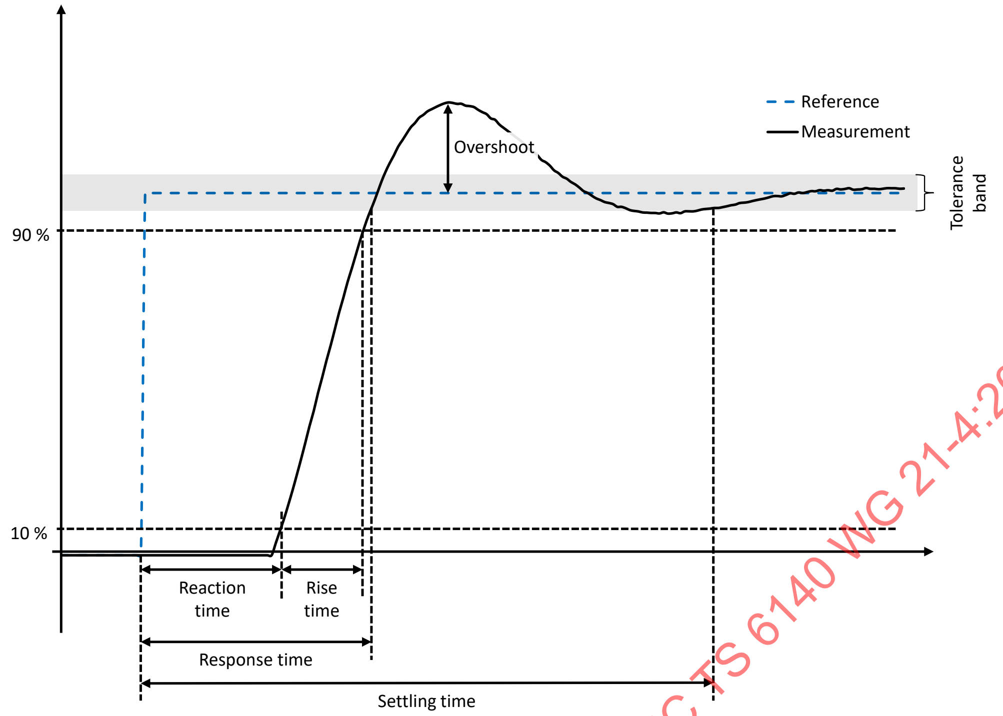


Figure 3 – Example of step response

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

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):

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

3.52
sub-group total harmonic voltage distortion - $THDS_{U_n}$ (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]

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:

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

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]

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

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

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

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				

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.

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.

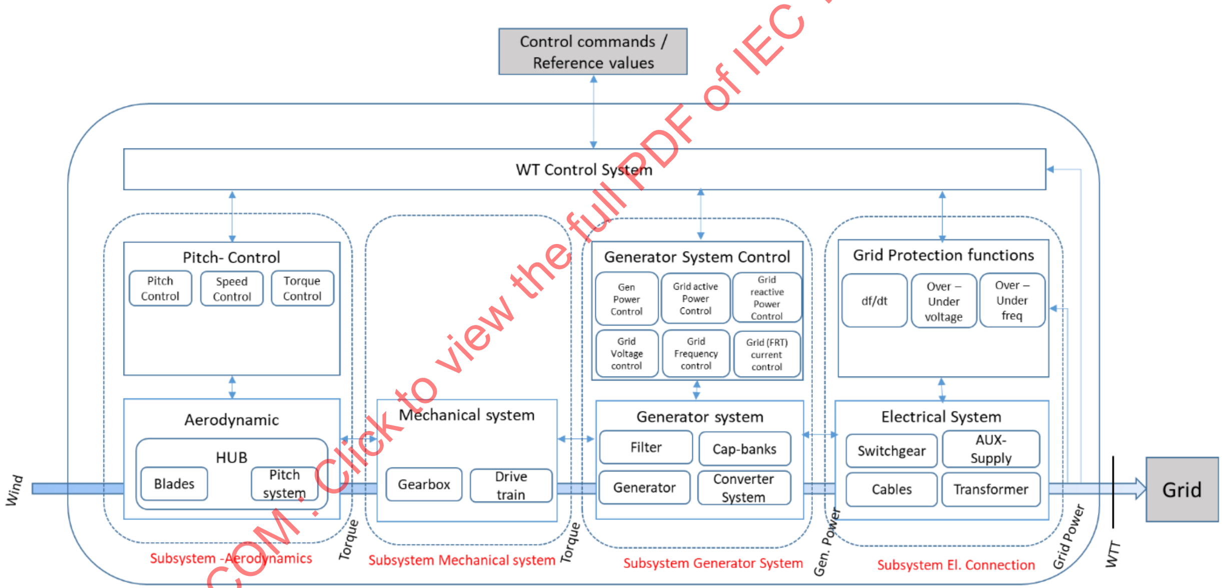


Figure 4 – Generic structure of WT

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	

	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

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

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

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

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.

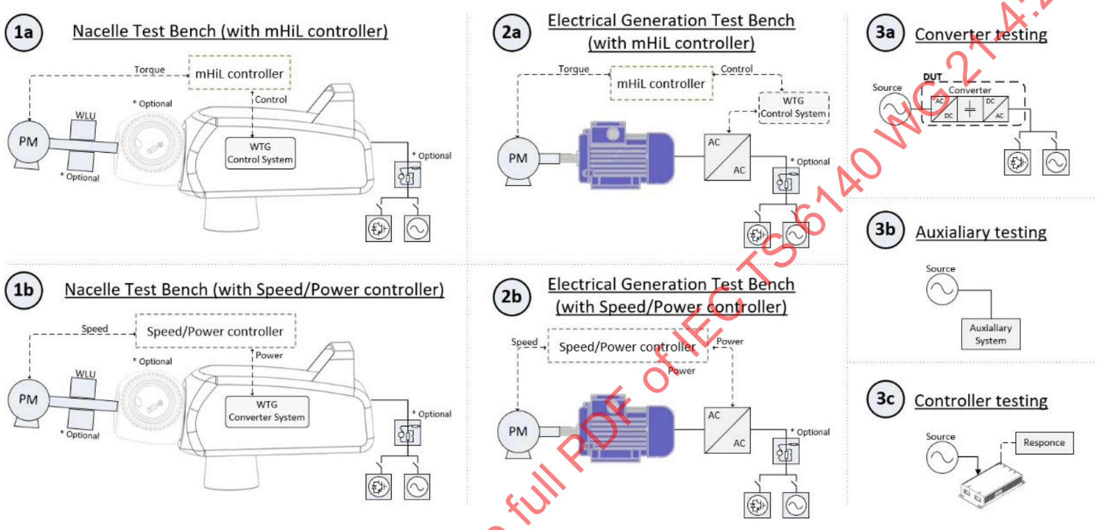


Figure 5 - Examples of Nacelle Test Benches type 1a, 1b to the left. Examples of Electrical Generation Test Benches type 2a, 2b in the middle and examples of component test benches type 3a, 3b, 3c to the right.

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.

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.

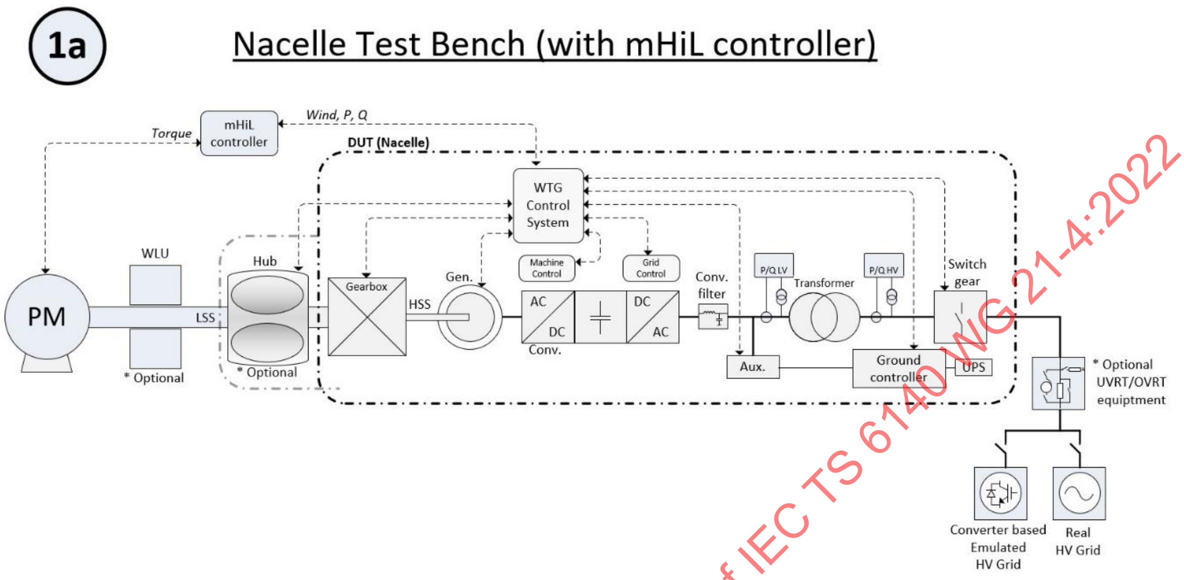


Figure 6 – Example of Nacelle Test Bench in mHiL control mode (1a)

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.

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.

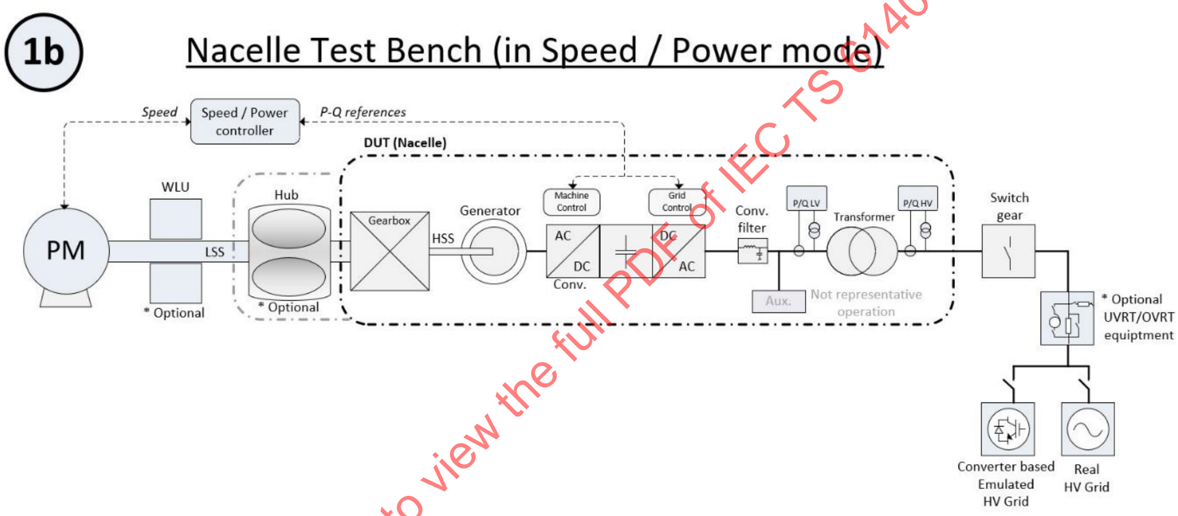


Figure 7 - Example of Nacelle Test Bench in Speed / Power control mode (1b)

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.

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

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.

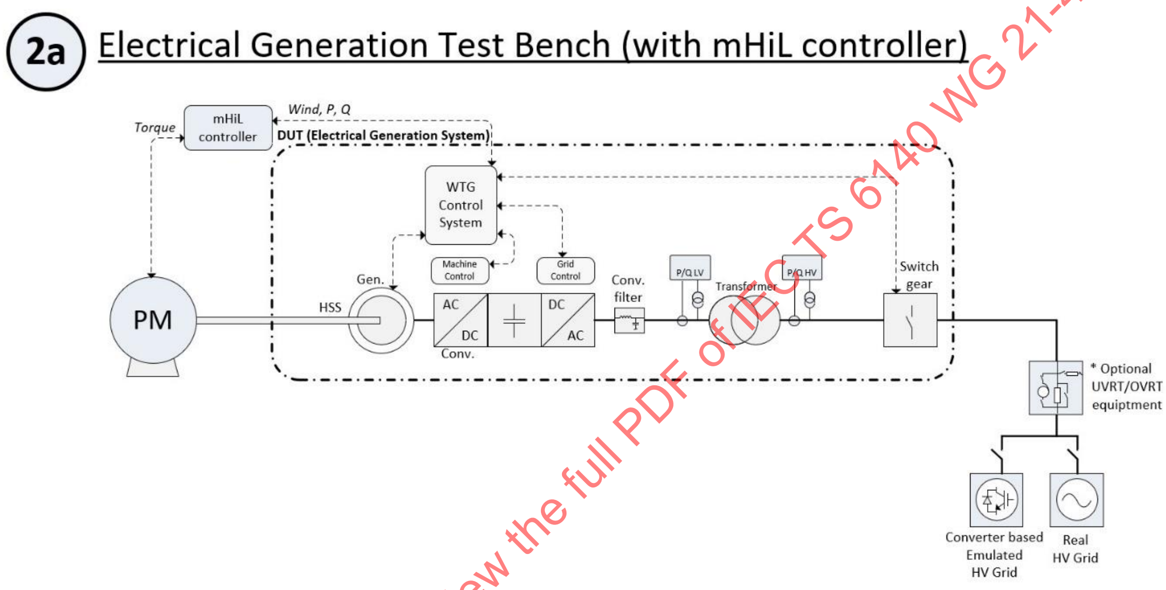


Figure 8 - Example of Electrical Generation Test Bench in mHiL control mode (2a)

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.

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.

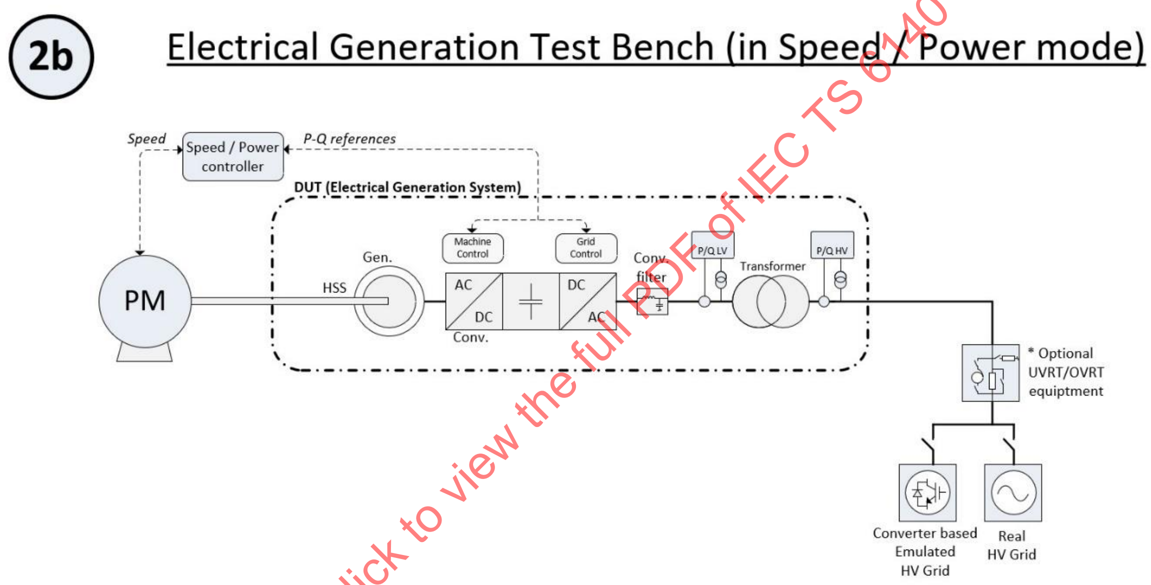


Figure 9 - Example of electrical generation test bench in speed / power control mode

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.

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.

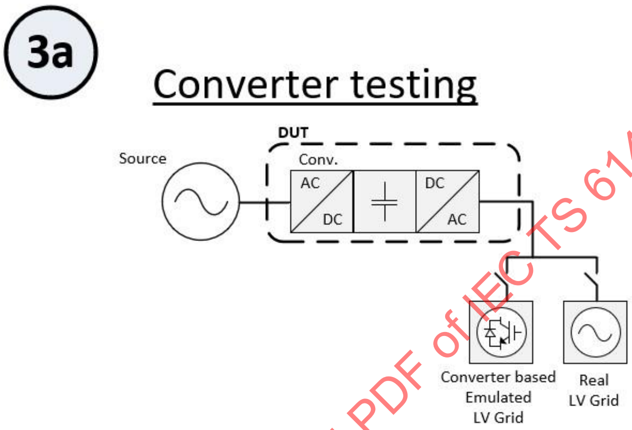


Figure 10 - Example of Converter Test Bench (3a)

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.

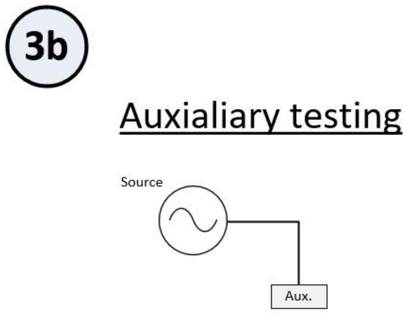


Figure 11 - Example of auxiliary test bench (3b)

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

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

7.4.2.1 Requirements for auxiliary test bench (3b)

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

7.4.3 Controller test bench (3c)

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

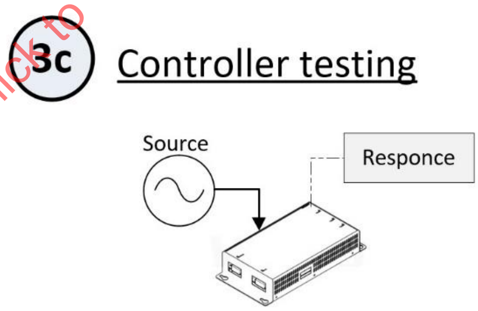


Figure 12 - Example of controller test bench (3c)

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

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

- Open loop control or
- Closed loop HiL control (HiL setup)

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

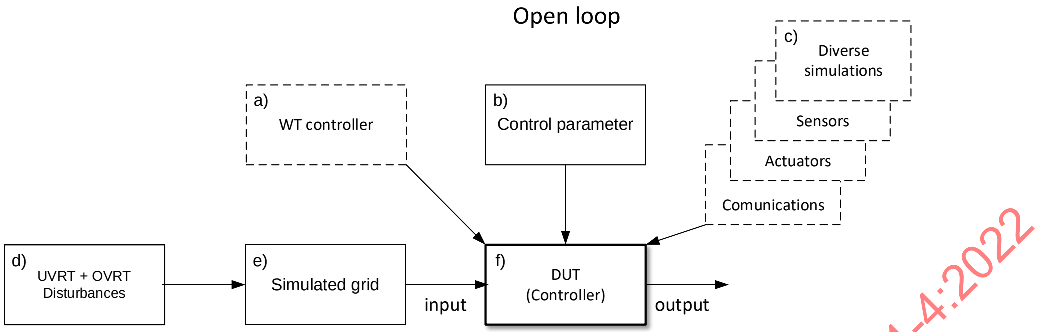


Figure 13 – Illustration of an exemplary test setup with open loop

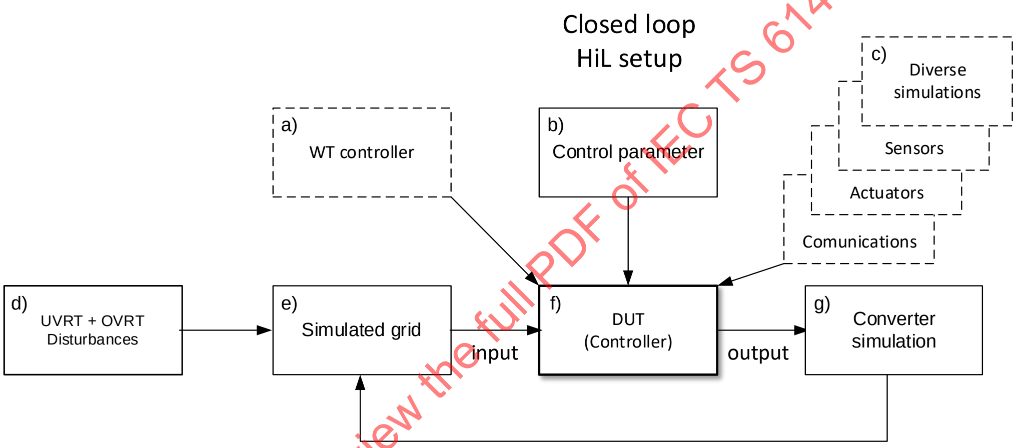


Figure 14 – Illustration of an exemplary controller-HiL test setup

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

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

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.

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.

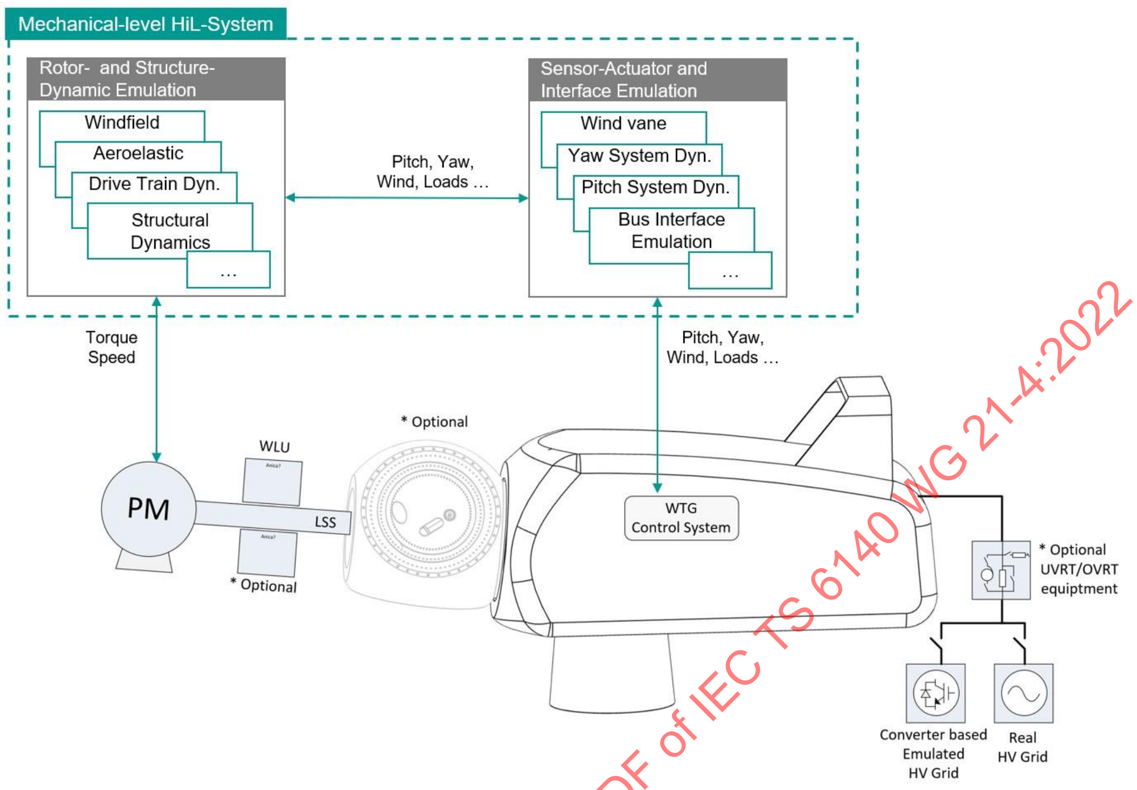


Figure 16 - General block diagram of the mechanical Hardware-in-the-Loop system required to operate nacelle or Electrical Generation System in mHiL-mode.

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

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	

• 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

7.5.1.3 Validation procedure

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

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

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

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

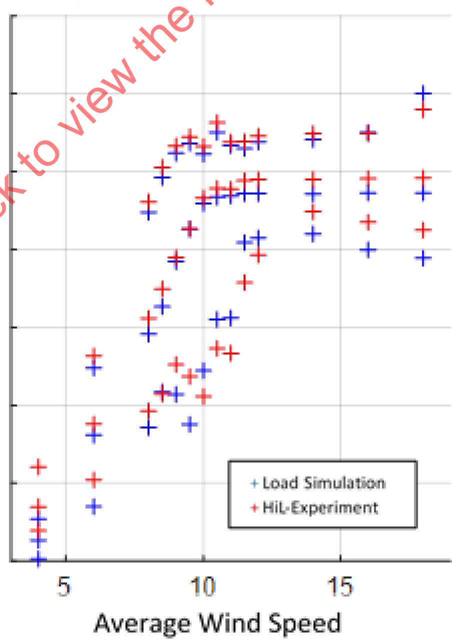


Figure 17 - Suggested reporting on comparison between mHiL-operated test bench and load simulation.

7.5.2 Prime mover for test benches

A prime mover (PM) can be one or more electric direct drive or high/medium speed motors, or one or more electrical high speed motors with a slave gearbox. The prime mover is applying torsional torque to the nacelle or generator via a Low Speed Shaft (test bench type 1) or high speed shaft (test bench type 2). Optionally a Wind Load Unit (WLU) applies wind loads (bending/yaw moments and thrust/radial forces). The test bench's low or high speed system can also include a misalignment and/or safe set coupling (mechanical fuse).

7.5.3 UVRT/OVRT HW equipment for test benches

The test bench can be equipped with suitable test equipment to perform UVRT and OVRT tests. Many topologies allow testing the behaviour of the WT in case of an under voltage or an over voltage event. However, three main solutions have become established, the shunt impedance or voltage divider based test equipment, the variable transformer and the full converter.

7.5.3.1 Voltage divider based test equipment

The voltage divider-based test equipment is a basic compliance test topology, which is referred as an example in IEC 61400-21-1 for under voltage ride-through (UVRT) capability test. Recently, this structure has been adapted for over voltage ride-through (OVRT) capability test as well. This test equipment has proven to be a useful tool in the early stages of grid integration research and characterization of utility-scale wind power. However, it has certain fundamental limitations, such as dependence on a stronger point of interconnections and an inability to replicate any evolving grid characteristics. Furthermore, it is limited in the achievable dip-levels, since it is based on tapping possibilities of the individual components.

The voltage divider-based test equipment is placed in between the WT and the WTT. It consists of a series and a short circuit impedance. Both impedances consist of interconnected coils. By connecting the series impedance, the fault is decoupled from the rest of the power grid. The short-circuit impedance is activated by a switch. This switch can be a mechanical circuit breaker or an electronic circuit breaker.

7.5.3.2 Full converter based grid emulator

Converter based grid emulators offer an alternative way of generating voltage dips. In contrast to the voltage divider-based equipment, the voltage dip is emulated by the converter (active component) and not physically generated by passive components. The connection of the grid emulator is between the grid connection of the test bench and the WT, as described in Figure 6. The grid emulator emulates the desired voltage behaviour at the WTT. Voltage dip depth and duration are freely adjustable. This solution makes it possible to generate any type of grid fault at different frequencies. The converter system needs to be oversized to ensure the UVRT testing of Type 3 WTs. In order to perform OVRT capability test using a converter-based grid emulator, step-up tap transformers can be used to generate the required over-voltage ranges.

Requirements for converter-based grid emulator

Table 5 -Requirements for Converter-based Grid Emulator

Operation mode	Requirements	Description
Steady state operation	Voltage and Frequency requirements	1. The Grid emulator shall be able to generate three phase-to-neutral voltages at the terminals of DUT.

		2. The Grid Emulator shall be able to adjust the voltage with an accuracy of +/- 1.5% and the frequency with an accuracy of +/- 1.5%.
	Current requirements	For steady state operation it is recommended the emulator has nominal current capability 1,2 p.u. compared to nominal current of the turbine (20% more). (trip level DUT converter)
	Background harmonics:	It is desirable that the grid emulator has minimum voltage background noise as possible in the whole range of the bandwidth 100HZ – 9kHZ
	Harmonic Injection:	This part is an optional application of grid emulator.
	Short circuit power of grid emulator:	The grid emulator will have a natural impedance by the HW components and an emulated impedance. This total short circuit impedance will determine the short circuit power of the emulator. Requirements for the level is found under SCR below.
	Short Circuit Ratio:	The short circuit power of the emulator should be high enough to achieve a SCR>2 in relation to the DUT nominal power. Recommended to implement configurable SCR based on the voltage control of emulator.

Dynamic requirements for the grid emulator

Operation mode	Requirements	Description
Dynamic requirements	• Rate of change of voltage (RoCoV):	The grid emulator should be able to simulate over-voltage or under-voltage events very fast according to the IEC 61400-21-1 figure 16 and figure 17.
	• Over-current capability:	Over-sizing of grid emulators for this purpose can be necessary for UVRT testing of Type 3 WTs to handle higher levels of short circuit current contributions.
	• General Dynamic Emulations	The grid emulator shall be able to generate voltages with variable amplitudes, variable frequency and phase jumps
	• Controllable Dynamic Impedance:	This part is an optional application of grid emulator.

7.5.3.3 Grid emulator in combination with the voltage divider based equipment

Another possibility is the combination of the grid emulator with the shunt impedance based VSG. The voltage divider based test equipment is placed between the grid emulator and the WT. The combination of the two test devices enables the converter system of the grid emulator to be considerably smaller since the over-sizing for the UVRT tests of type 3 WTs is no longer necessary. Nevertheless, it is possible to emulate different grid connection points and deviations of the grid frequency.

7.5.3.4 Autotransformer based test equipment

A variable output transformer or autotransformer is another test equipment to perform UVRT or OVRT tests. It is a transformer in combination with appropriate switching units to connect another transformer output level to the load. Switching to a different combination of taps determines the type of fault as well as the depth of the voltage dip.

7.5.3.5 Requirements for the UVRT / OVRT HW equipment

- Voltage dip depths adjustable according to IEC 61400-21-1
- Duration of the voltage dips adjustable according to IEC 61400-21-1
- In the case of unbalanced faults, the phase relationship on the high voltage side of the WT transformer should correspond to fault type C according to [2].

7.5.4 Measurement systems for test benches

The measurement system and equipment used to acquire data from test benches must be chosen with a sufficient accuracy, following the requirements in IEC 61400-21-1.

For both voltage and current transducers Class 1.0 is required.

For the data acquisition sufficient sampling frequency must be chosen depended on the test campaign, as defined in IEC 61400-21-1.

8 Measurement and test of electrical characteristics as defined in 61400-21-1

This chapter defines the 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 a risk evaluation for the transferability of the test results towards the WT.

8.1 Power Quality aspects

8.1.1 Flicker during continuous operation

For testing the flicker emission of a wind turbine sufficiently, flicker shall be tested in the field.

Note: The flicker emission of a wind turbine can be influenced by many of its components, whereby the interaction of these components is also significant. Some of these components are rotor blades, drivetrain, generator, converter system, control system including pitch and speed control and control of active and reactive power, auxiliary supplies etc.

8.1.2 Flicker and voltage change during switching operations

For testing the flicker and voltage change during switching operations of a wind turbine sufficiently, tests shall be performed in the field.

Note: The flicker and voltage change during switching operations of a wind turbine can be influenced by many of its components, whereby the interaction of these components is also significant. Some of these components are rotor blades, drivetrain, generator, converter system, control system including pitch and speed control and control of active and reactive power, auxiliary supplies etc.

8.1.3 Harmonics

8.1.3.1 Description

The aim of this performance test is to determine the emission of voltage and current harmonics, interharmonics and higher frequency components of a DUT during continuous operations according to IEC 61400-21-1 on subsystem or component level.

Further tests and analysis can be performed according to Annex D of IEC61400-21-1.

8.1.3.2 Test setup & test conditions

Two options are available for measuring the harmonics on a test bench:

- Option 1: Measurement of harmonics on test bench with grid emulator.
- Option 2: Measurement of harmonics on test bench with a connection of the DUT to the public grid.

The following requirements are placed on the DUT for the measurement of harmonics on a test bench:

- The following components have to be taken into account for the performance test according to Annex B.2
  - Converter system
  - Generator
  - Additional Cap-banks for reactive power compensation (eg for Type 1 or 2 WTs)
  - Filter
  - Grid active power control
  - Grid reactive power control

- Generator power Control (or speed control)
- Transformer
- Drivetrain

The measurement shall at least be performed on a category 2b test bench as described in chapter 7 and meet the following characteristics:

- The DUT shall operate within the active power bins 0%, 10%, 20%,.., 100% P_n.
- The grid emulator has to fulfill the following requirements for the measurement of the sub-grouped harmonic voltages at no load condition (see Table 6). The measurement has to be done according to IEC 61000-21-1.
- In case of the connection of the DUT to the public grid (see option 2), the test conditions of IEC61400-21-1 shall be applied.

Table 6 - Harmonic emission limits of the grid emulator at no load (disconnected DUT)

Odd harmonics non-multiple of 3		Odd harmonics multiple of 3		Even harmonics	
Harmonic order h	**Harmonic voltage %**	**Harmonic order h**	**Harmonic voltage %**	**Harmonic order h**	**Harmonic voltage %**
5	1,5	3	1,25	2	0,4
7	1,25	9	0,6	4	0,4
11	0,7	15	0,3	6	0,4
13	0,6	21	0,3	8	0,4
17≤h≤49	0,4	21<h≤49	0,3	10<h≤49	0,4
$THDS_{U,50}$ shall be below 2% up to 50th harmonics, $THDS_{U,180}$ up to 180th harmonics shall be below 3%.					

Note: The limits in Table 6 are based on no-load voltage requirement for LV (IEC61000-4-7). The compatibility level is the same for LV and MV according IEC61000-3-6 and IEC61000-2-4 (class 2).

If the grid emulator does not fulfill the required limits of Table 6, or the public grid does not fulfil the required test conditions as given in IEC61400-21-1 then the influence of the background noise on the DUT harmonics shall be eliminated, either by following Annex E or by other methods, e.g. as given in Annex D of IEC 61400-21-1 for public grid connection. The method used shall be described in the report.

The upstream fundamental frequency short-circuit impedance seen from the DUT's grid side converter(s) (including all passive components of the DUT and the grid emulator), shall be in the range of 5% - 30% considering as base power the nominal power of the DUT.

Note: The test conditions described above are required in order to obtain reliable test results and should not be viewed as conditions for a reliable connection to the energy supply network and for the operation of the DUT.

8.1.3.3 Test & measurement procedure

Background noise measurement:

- Before the measurement for option 1 or option 2 can be started, a background noise measurement shall be done. For this purpose, the DUT is disconnected from the grid emulator or the public grid.
- One 10-minute data set of instantaneous voltage measurement shall be measured.

Measurement procedure for option 1 (see 8.1.3.2):

- Set point reactive power: Q= 0 var.
  Optional: reactive power under- and overexcited at the maximum power bin.
- Three 10-minute data sets of instantaneous voltage and current measurements shall be collected for each 10% power bin (0% Pn – 100% Pn) as the same modulation index as in the no load tests.
- The maximum value from the three measurements and three phases of each power bin shall be taken.

Measurement procedure for option 2 (see 8.1.3.2):

- Set point reactive power: Q= 0 var.
  Optional: reactive power under- and overexcited at the maximum power bin.
- Seven, 10-minute data sets of instantaneous voltage and current measurements shall be collected for each 10% power bin (0% Pn – 100% Pn) as the same modulation index as in the no load tests.
- The 95 percentile from the seven measurements and three phases of each power bin shall be taken.

Note: All three phases shall be measured at the same time during the measurements for both options.

A 10-cycle window for 50 Hz and 12-cycle window for 60 Hz power systems is recommended for the analysis of measurements. The window size shall be stated in the report.

Harmonic currents below 0,1% of I_n for any of the harmonic orders need not be reported.

The Discrete Fourier Transformation (DFT) is applied to each of the measured currents and voltages with rectangular weightings. The active power shall be evaluated over the same time window as the harmonics.

The THC and $THDS_{U,50}$ distortion for each 10-cycle window for 50 Hz and 12-cycle window for 60 Hz shall be calculated.

The 10-minute square root of the harmonic mean of the squared 10-cycle (for 50 Hz power systems) or 12-cycle (for 60 Hz power systems) window values of each frequency band (i.e. each sub-group harmonic, sub-grouped centered interharmonic, higher frequency current and voltage component and THC and $THDS_{U,50}$) shall be calculated for each 10-minute time-series.

If harmonics, interharmonics or higher frequency components are clearly influenced by background distortion, then in case of option 1 (see 8.1.3.2) the procedure of Annex E could be followed by calculating the DUT harmonic exclusive the background noise. In case of option 2 (see 8.1.3.2) Annex D of IEC 61400-21-1 could be followed.

8.1.3.4 Documentation

The emission of current and voltage harmonics, interharmonics and higher frequency components shall be documented in tables and graphs as shown, for example, in Annex A.

The following parameters shall be given in tables in percentage of U_n for background measurement:

- voltage harmonics
- voltage interharmonics
- higher frequency voltage components
- $THDS_U$ up to the 50th harmonic order

The following parameters shall be given in tables in percentage of I_n or U_n and for operation of the DUT within the active power bins 0%, 10%, 20%, …, 100% of Pn. (Note: The 0, 10, 20,…, 100% are the bin midpoints) for measurements according to IEC 61400-21-1.

Option 1 (see chapter 8.1.3.2):

- Max value of current and voltage harmonics
- Max value of current and voltage interharmonics
- Max value of higher frequency current and voltage components
- Max value of THC up to the 50th harmonic order
- Max value of $THDS_U$ up to the 50th harmonic order

Option 2 (see chapter 8.1.3.2):

- 95th percentile of current and voltage harmonics
- 95th percentile of current and voltage interharmonics
- 95th percentile of higher frequency current and voltage components
- 95th percentile of THC up to the 50th harmonic order
- 95th percentile of $THDS_U$ up to the 50th harmonic order

The following information shall be given for the test:

- Impedance of the grid emulator up to at least 50th harmonic order and if possible, up to 180th harmonic order (including the output transformer, filter and converter of the grid emulator)
- Impedance of the transformer and the rest passive components of the DUT

Optionally, prevailing phase angles and ratio may be also included, following IEC 61400-21-1:2019 Annex D.

8.1.3.5 Transferability of test results

The test results can replace full-scale wind turbine measurements of harmonics.

8.2 Steady state operation

The steady-state operation chapter consists of the steady state measurements in relation to maximum power, reactive power capability, unbalance factor etc.

Measurements shall be sampled during steady-state operation only, i.e.: after having reached settling time according to IEC 61400-21-1.

8.2.1 Maximum power

8.2.1.1 Description

The aim of this performance test is to show that the specified value of the active power output is kept constant in normal operation over different averaging time.

The maximum measured power of the wind turbine shall be specified as a 600 s average value, P_{600}, a 60 s average value, P_{60} and as a 0,2 s average value, $P_{0,2}$. The maximum active power peaks are determined from each of the different averaging intervals.

8.2.1.2 Test setup & test conditions

The measurement shall at least be performed on a category 1a test bench as described in chapter 7. The test bench system shall provide torque variations according to the defined wind classes of the DUT and under simulated normal wind speed variations and distributions as described in IEC 61400-1

The DUT shall include at least the components and control functions as defined in Annex B.2.

8.2.1.3 Test & measurement procedure

The overall procedure described in IEC 61400-21-1 section 8.3.3.2 shall be applied.

The test shall be performed at full load with nominal power P_n and with simulated wind speed around the nominal wind speed according to the defined wind classes of the DUT and under normal wind speed variations and distributions as described in IEC 61400-1.

8.2.1.4 Documentation

The variables given in IEC 61400-21-1 section 8.3.3.3 shall be calculated.

The data, tables and figures given in IEC 61400-21-1 section 8.3.3.3 and Annex A shall be documented.

8.2.1.5 Transferability of test results

The test results can replace full-scale wind turbine measurements of maximum power.

8.2.2 Reactive power characteristic (Q = 0)

8.2.2.1 Description

The aim of this measurement is to determine reactive power characteristic of the WT - DUT for a reference value of Q = 0.

8.2.2.2 Test setup & test conditions

The measurement shall at least be performed on a category 2a test bench as described in chapter 7. The test bench system shall provide torque variations according to the defined wind classes of the DUT and under simulated normal wind speed variations and distributions as described in IEC 61400-1.

The DUT shall include at least the components and control functions as defined in Annex B.2.

Different from the general requirement above, for type IV wind turbines, the test can be performed without generator, on a category 3a test bench.

8.2.2.1 Procedure

Measurements shall be sampled during steady-state operation only.

The procedure described in IEC 61400-21-1 section 8.3.4.2 shall be applied, with the following exceptions:

- measurements shall be taken so that at least one 1-minute time-series of active and reactive power are collected at each 10 % power bin.

8.2.2.2 Documentation

The variables given in IEC 61400-21-1 section 8.3.4.3 shall be calculated.

The data, tables and figures given in IEC 61400-21-1 section 8.3.4.3 and Annex A shall be documented.

8.2.2.3 Transferability of test results

The test results can replace full-scale wind turbine measurements of reactive power characteristics.

8.2.3 Reactive power capability

8.2.3.1 Description

The aim of this measurement is to determine the under- and overexcited reactive power capability of the WT as a function of the active power output.

8.2.3.2 Test setup & test conditions

The measurement of reactive power capability shall at least be performed on a category 2b test bench as described in chapter 7.

The DUT shall include at least the components and control functions as defined in Annex B.2.

Different from the general requirement above, for type IV wind turbines, the test can be performed without generator, on a category 3a test bench.

8.2.3.3 Procedure

Measurements shall be sampled during steady-state operation only.

The procedure described in IEC 61400-21-1 section 8.3.5.2 shall be applied, with the following exceptions:

- measurements shall be taken so that at least one 1-minute time-series of active and reactive power are collected at each 10 % power bin;

8.2.3.4 Documentation

The variables given in IEC 61400-21-1 section 8.3.5.3 shall be calculated.

The data, tables and figures given in IEC 61400-21-1 section 8.3.5.3 and Annex A shall be documented.

8.2.3.5 Transferability of test results

The test results can replace full-scale wind turbine measurements of the reactive power capability.

8.2.4 Voltage dependency of PQ diagram

8.2.4.1 Description

The dependency on the voltage variations at the DUT terminals should be documented according to the manufacturer's specification. The PQ diagram should be repeated for the maximum and minimum continuous operation voltage for the wind turbine according to the manufacturer's specification.

8.2.4.2 Test setup & test conditions

The measurement shall at least be performed on a category 2b test bench as described in chapter 7.

The grid system shall be able to provide a variable stable voltage supply during the test (e.g. by a grid emulator).

The DUT shall include at least the components and control functions as defined in Annex B.2.

Different from the general requirement above, for type IV wind turbines, the test can be performed without generator, on a category 3a test bench.

8.2.4.3 Test & measurement procedure

Measurements shall be performed at each active power bin from 10 % to 100 % of P_n. The procedure as defined in IEC 61400-21-1: 2019, chapter 8.3.6.2 shall be applied.

8.2.4.4 Documentation

The variables given in IEC 61400-21-1:2019 section 8.3.6.3 shall be calculated.

The data, tables and figures given in IEC 61400-21-1:2019 section 8.3.6.3 and Annex A shall be documented.

Note: In order to gain higher resolution in certain areas of the PQ diagram, additional measurements can be carried out defining intermediate points within a power bin with the desired resolution.

8.2.4.5 Transferability of test results

The test results can replace full-scale wind turbine measurements of voltage dependency PQ-diagram.

8.2.5 Unbalance factor

8.2.5.1 Description

The aim of the measurement is to determine the current unbalance factor in the wind turbine drive train mounted in a test bench.

8.2.5.2 Test setup & test conditions

The measurement shall at least be performed on a category 2b test bench as described in chapter 7.

For the determination of the current unbalance factor, the voltage unbalance factor of the grid or of the grid emulator shall be as low as possible, at least less than 1% during the entire test (1 min averages).

The DUT shall include at least the components and control functions as defined in Annex B.2

8.2.5.3 Test & measurement procedure

For the determination of the current unbalance factor the procedure below shall be followed:

The test shall be done in 10 steady states where the torque is controlled to give active power in steps of 10%, from 10% to 100%. The drivetrain shall be in a steady state for minimum 1 minute in each step. The positive sequence reactive power shall be set to zero. 3-phase voltage and currents shall be recorded, and 1-minute averages of voltage and current unbalances shall be calculated in each step.

The positive sequence voltage U_1 and current I_1 as well as the negative sequence voltage U_2 and current I_2 shall be calculated according to IEC 61400-21-1.

8.2.5.4 Documentation

The measured 1-minute values of the current unbalance and the active power positive sequence system component are represented as an IUF versus active power diagram. The measurement results shall be presented in a table as mean values of each power bin, as defined, for example, in Table 8.2). The maximum current unbalance factor as a 1-minute value shall be explicitly given.

Table 7 - Current unbalance factor

P [p.u.]	Q [p.u.]	U1 [p.u.]	U2 [p.u.]	UUF	I1 [p.u.]	I2 [p.u.]	IUF
~0,1	~0,0						
~0,2	~0,0						
~0,3	~0,0						

~0,4	~0,0						
~0,5	~0,0						
~0,6	~0,0						
~0,7	~0,0						
~0,8	~0,0						
~0,9	~0,0						
~1.0	~0,0						

8.2.5.5 Transferability of test results

The test results can replace full-scale wind turbine measurements of unbalance.

8.3 Control performance

8.3.1 Active power control

8.3.1.1 Description

The ability of the wind turbine to operate in active power control mode shall be characterized for various reference values given by the control interface. The aim of this test is to determine the response of the WT to reference commands regarding the static error, the rise time and the settling time of active power, for both steady-state conditions and under dynamic response conditions.

8.3.1.2 Test setup & test conditions

The test shall at least be performed on a category 2a test bench test setup according to chapter 7. The test shall be carried out in the wind speed range from the cut_in and cut_out wind speed, in the power range of the DUT from 0 to 100 % and can be carried out in simulated laminar wind conditions.

The DUT shall include at least the components and control functions as defined in Annex B.2.

8.3.1.3 Test & measurement procedure

Static error test

For the test of the static error, the following test procedure is recommended: a reference value shall request active power reduction from 1,0 p.u. to 0,20 p.u. in steps of 0,20 p.u. with at least 2-minute operation at each reference value in accordance with IEC 61400-21-1: 2019 chapter 8.3.4 - Figure 8.

The calculation of the 1-minute block-average values for the test report shall be carried out after steady state is reached. The time of steady state will be defined as the last 1 minute at each step.

- The absolute static error of the active power shall be measured.
- The simulated wind speed should be such that the available active power output of the DUT is at least 0,1 p.u. higher than the targeted reference value, but not less than 0,5 p.u. during the entire test procedure. For the reference value of 1,0 p.u. the WT shall operate with nominal active power.
- The test has to be carried out continuously, i.e. it is not allowed to connect disjoint measurements.
- The sampled data for the active power shall be one fundamental period average data.

Dynamic response test – step down

This test will be used to determine the dynamic behaviour of the WT by observing the step response characteristics (i.e. settling time, ramp-down time, reaction time). For this test a step of the active power reference with a minimum step size of 0,4 p.u. of the nominal active power is commanded, according to Figure 18.

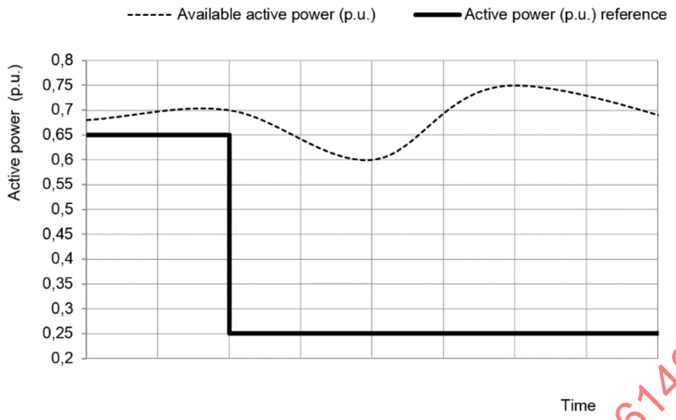


Figure 18 - Example of active power response step

- The tolerance band is ±0,05 p.u. for the calculation of the settling time.

  The sampled data for active power shall be calculated over one fundamental period (average data).

  Ramp rate limitations shall be deactivated during the test. If this is not possible, the ramp rate limitation has to be adjusted to the highest value (that causes the fastest reaction of the WT).

Dynamic response test – step up

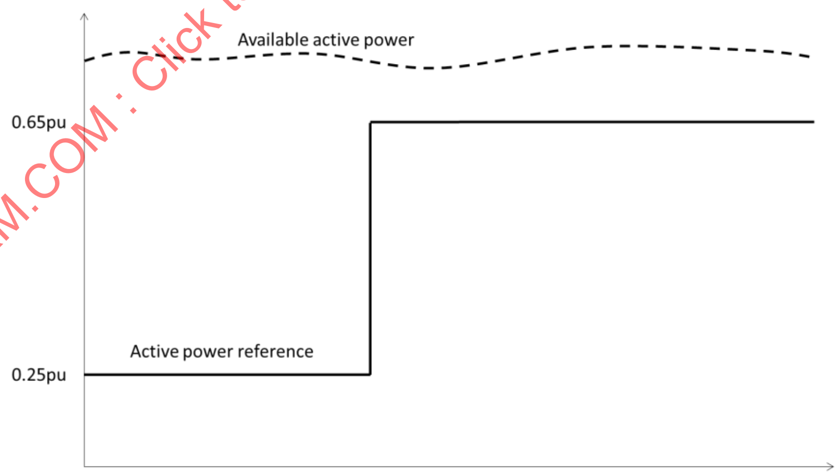


Figure 19 - Active power dynamic step response

This test will be used to determine the dynamic behaviour of the DUT by observing the step response characteristics (i.e. settling time, ramp-up time, reaction time). For this test a step of the active power reference with a minimum step size of 0,4 p.u. of the nominal active power is commanded, according to Figure 19.

- The tolerance band is ±0,05 p.u. for the calculation of the settling time.
- The sampled data for active power shall be calculated over one fundamental period (average data).

  Ramp rate limitations shall be deactivated during the test. If this is not possible, the ramp rate limitation has to be adjusted to the highest value (that causes the fastest reaction of the WT).

- The available power value that is internally calculated by the WT according to the given wind speed and other internal parameters will be provided for measurement.

8.3.1.4 Documentation

The following parameters shall be calculated and documented in a test report:

Time-series of:

- Reference values sent to the DUT as P (p.u.)
- Simulated wind speed given to the DUT/WT and the test bench
- Available active power provided by the DUT controller
- Measured positive sequence active power output at the grid connection point

8.3.1.5 Transferability of test results

The test results provide an overview of the control performance in relation active power control.

The test results can replace full-scale wind turbine measurements.

8.3.2 Active power ramp rate limitation

8.3.2.1 Description

The aim of this measurement is to show the capability of the WT to follow given active power gradients, with positive and negative ramp rate:

The manufacturer shall declare the possible settings (reference values or setting range) of the ramp rates of the WT. The tests shall be adapted to the possible settings of the ramp rates of the WT.

8.3.2.2 Test setup & test conditions

The measurement shall at least be performed on a category 2a test bench as described in chapter 7.

The test shall be carried out in the wind speed range from the cut_in and cut_out wind speed and in the power range of the DUT from 0 to 100 % and can be carried out in simulated laminar wind conditions.

The DUT shall include at least the components and control functions as defined in Annex B.2.

8.3.2.3 Test & measurement procedure

- The simulated wind speed shall be high enough for active power production higher than 0,7 p.u. for the entire test.
- Data should be recorded from 10 s before the ramp rate command and until steady state condition is reached.

- At the beginning of the test, the DUT shall be operated in normal operation mode. The active power of the WT can be set to an adequate start value above 0,5 p.u. of the nominal active power. Then the following two tests with different ramp rates shall be performed.
- Test 1 (slow ramp rate), e.g. +/- 10 % P_n /minute
- Test 2 (fast ramp rate), e.g. +/- 2 % P_n /s
- The test shall be carried out with at least P=0,2 p.u. of the nominal active power between each reference value.

8.3.2.4 Documentation

The ability of the DUT to operate in ramp rate limitation control mode shall be characterized by test results presented in a graph. The graph shall show the available and measured active power output during the operational state. Figure 20 gives an example of a step with a negative ramp rate and of a step with a positive ramp rate. The steps are achieved by switching the DUT from one reference value to another reference value and back.

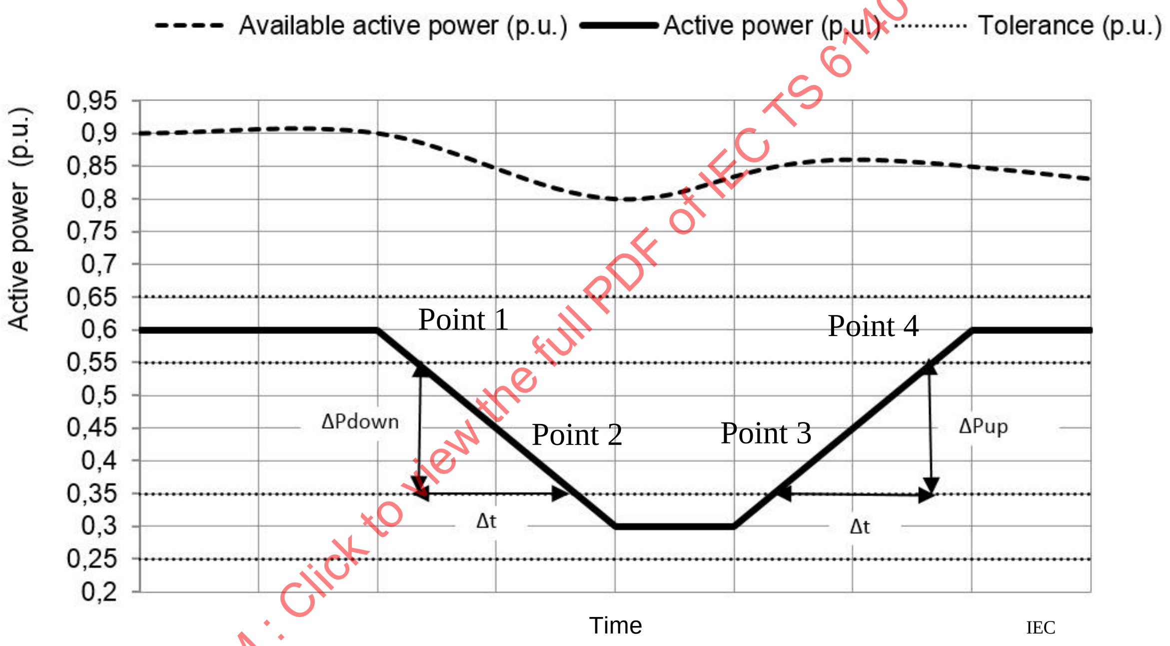


Figure 20 - Example of available active power and active power in ramp rate limitation mode

The positive and negative active power gradient shall be calculated from the 0,2 s average of the measured active power from respectively two different points during the ramp rate activation (point 1 and point 2 for the calculation of the negative gradient and point 3 and point 4 for the calculation of the positive gradient, in accordance with Figure 20.

Table 8 - Active power ramp rate calculation

	Requested reference value P_{set} [p.u.]	Requested active power ramp rate $\Delta P/\Delta t$ [p.u./s]	Measured active power ramp rate $\Delta P/\Delta t$ [p.u./s]
Point 1			
Point 2			

Point 3			
Point 4			

- Requested and measured ramp rate characteristic shall be given in the test report in accordance with Table 8.
- The available and measured active power output shall be represented in a graph in accordance with Figure 20.
- A declaration of the ramp rate setting procedure by the manufacturer shall be described in the test report.

The following parameters shall be calculated and documented in a test report:

Time-series of:

- Active power reference values sent to the DUT in p.u.
- Simulated wind speed given to the DUT and the test bench
- Available active power provided by the DUT controller
- Measured positive sequence active power output at the grid connection point

8.3.2.5 Transferability of test results

The test results provide an overview of the control performance in relation active power control.

The test results can replace full-scale wind turbine measurements.

8.3.3 Frequency control

8.3.3.1 Description

With this test, the active power reduction as a function of the grid over-frequency shall be measured and documented.

NOTE The defined frequency test includes only over-frequency and no under frequency tests, as the described procedure mainly validate the functionality of the frequency control and not the real performance in relation to frequency changes. The underfrequency test can be performed in a similar way as defined in the procedure. The real frequency capability test is defined in chapter 9.2.2.

The wind turbine frequency dependent active power control capability shall be declared by the manufacturer and document in terms of e.g. dead band, slope, release conditions.

8.3.3.2 Test setup & test conditions

The measurement shall at least be performed on a category 2a test bench as described in chapter 7. In the wind speed range from cut_in to cut_out wind speeds, in the power range of the DUT from 0 to 100 % and under simulated laminar wind conditions.

The DUT shall include at least the components and control functions as defined in Annex B.2.

8.3.3.3 Test & measurement procedure

The procedure to test frequency control involves pairs of frequency and active power which begin from a starting point at "First measurement point" to the maximum possible frequency reference value at "step max" and back to the starting point "Step release control" according to the chosen function of the controller. The following tests verify the control capability of the WT to perform a frequency dependent power control, with a given gradient.

The Figure 21 shows an example of an active power control function $P = f(f)$.

It is up to the DUT manufacturer to define the kind of control function that shall be tested. The number of frequency steps and frequency values is variable and depends on the control function to be tested.

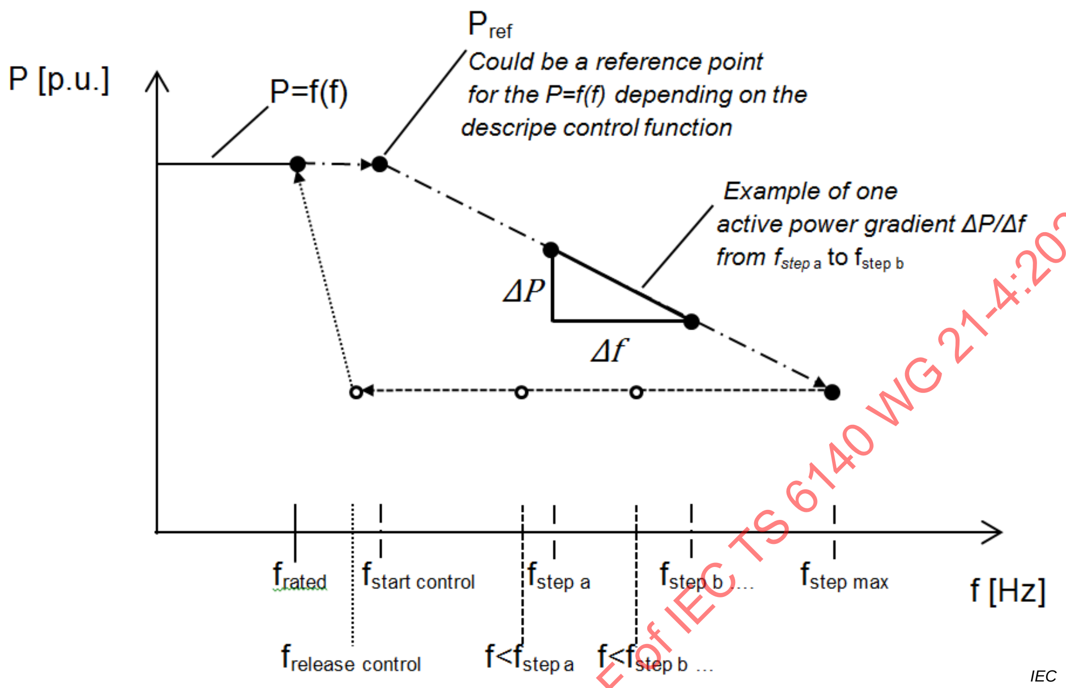


Figure 21 – Example of an active power control function $P=f(f)$, with the different measurement points and related steps of frequency

The test shall be performed at two different power levels, at

a) P > 0,8 p.u.

b) P between 0,25 p.u. and 0,5 p.u.

Each frequency step should be held for at least 30 seconds.

If the controller allows different settings concerning the response time or the delay time for the frequency-dependent active power reduction, then the fastest possible setting has to be chosen.

For the test itself, one of the following procedures shall be used:

a) Change the frequency of the grid, e.g. with a grid emulator.

b) Provide an internal or external input at the control unit to add a frequency reference value offset to the nominal frequency. The software shall be adapted to calculate a resulting frequency (nominal frequency + offset signal) and to react to this signal. For this test, also the additional offset shall be measured.

The grid protection settings of the DUT shall not be changed during the test.

8.3.3.4 Documentation

The following information shall be given:

- The frequency control function declared by the manufacturer
- Description of the test setup / Real time simulator setup
- Measurement setup according to chosen test procedure

The following parameters shall be documented in tables and graphs as shown in for example Annex A

- The measured frequency together with the reference signal has to be documented. The active power output of the DUT as block average time values (0,2 s) and the available active power have to be documented.
- The active power and the frequency change over time shall be presented in the report.
- The results of the test "frequency increase at nominal active power" have to be documented in a table. This includes the measured frequency and active power and the calculated active power gradient.
- The active power gradient between two consecutive measurement points shall be determined by calculation of $\Delta P/\Delta f$, as can be seen in Figure 21 as an example.
- The results of the test "frequency increase at partial power" have to be documented in a table. This includes the measured frequency and active power and the calculated active power gradient.
- The active power shall be plotted over the frequency increase. Frequency increase is the difference between the measured frequency and the nominal frequency of wind turbine.
- For nominal as well as for partial power, an average gradient of active power shall be calculated and reported based on the determined gradients given in Table 9.

Every change of parameter shall be documented.

Table 9 – Example of settings for the frequency dependent active power function

Step of the Measurement	Measured Grid frequency [Hz]	Frequency reference [Hz]	Measured Active power [p.u.]	Active power gradient [p.u./Hz]
First measurement point	f_{rated}	-----		-----
Step start control				
Step $f_{step\ a}$				
Step $f_{step\ b}$				
Step max				
Step $f < f_{step\ b}$				
Step $f < f_{step\ a}$				
Step release control				

.

8.3.3.5 Transferability of test results

The test results provide an overview of the control performance in relation to the frequency depended active power control.

The test results can replace full-scale wind turbine measurements.

8.3.4 Synthetic inertia

The aim of this test is to document the wind turbine ability to provide a synthetic inertia in the case of fast frequency events in the power system.

8.3.4.1 Description

The aim of the test is to determine the control performance of the Wind turbine to provide synthetic inertia in case of under frequency events, as basis for the simulation model of the Wind power plant.

8.3.4.2 Test setup & test conditions

The measurement shall at least be performed on a category 2a test bench as described in chapter 7. In the simulated wind speed ranges from the cut_in and cut_out wind speed, in the power range of the DUT from 0 to 100 % and can be carried out in simulated laminar wind conditions according to IEC 61400-1.

The grid emulator – shall be able to vary the frequency with a frequency change of minimum 5 Hz/s in the range of +/- 10 % of the nominal grid frequency. Alternative a simulated frequency signal shall be applied to the WT control system.

The DUT shall include at least the components and control functions as defined in Annex B.2.

8.3.4.3 Test & measurement procedure

The test shall be performed under the following conditions:

a) At partial load with an active power output of 0,3, 0,5, 0,8 and 1.0 P_n with an simulation of constant wind speed / fixed torque

b) At full load with 1,0 P_n with wind speed above 20 % of the nominal wind speed

c) At full load with 1,0 P_n with variating wind speed of +/- 10 % around the nominal wind speed. The wind speed shall decrease/ increase together with the frequency variation

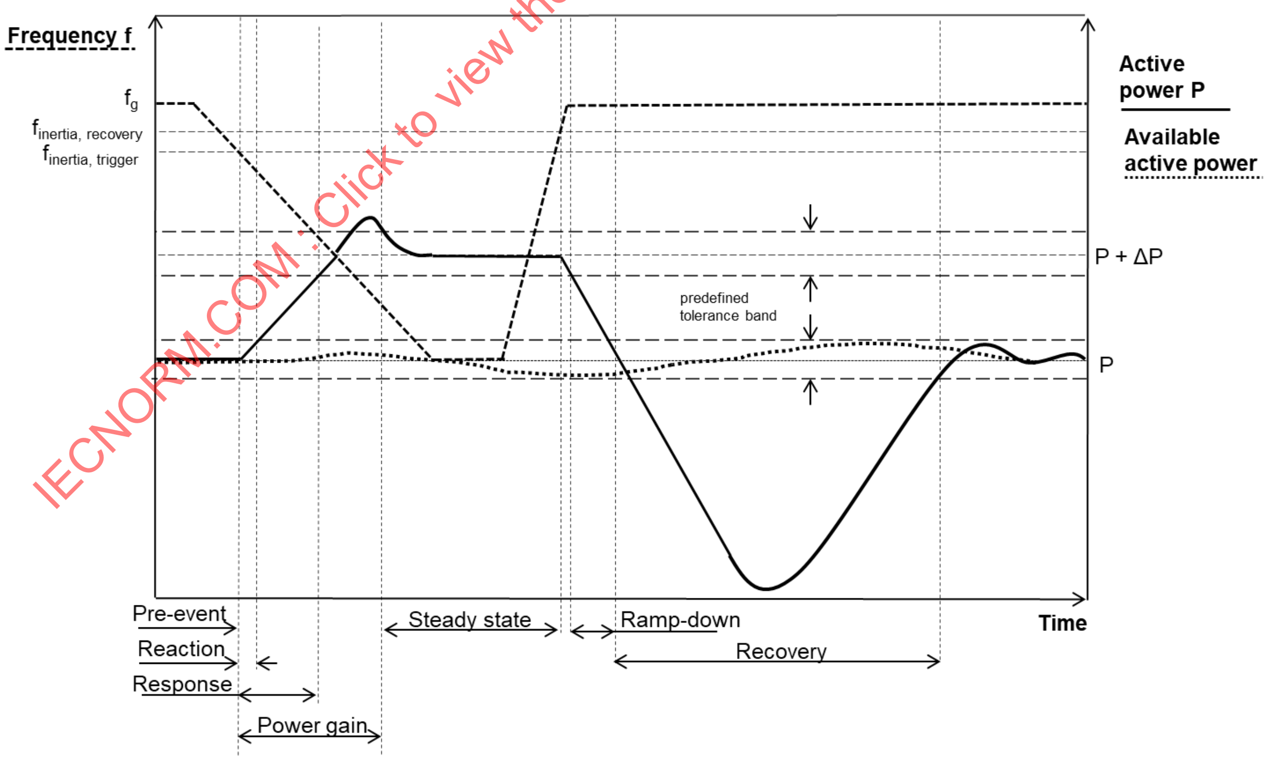


Figure 22 - Synthetic inertia – example response and definition

The stated response shall include results from at least 2 tests for each case - a, b and c.

The analysis of the measurement consists of 4 intervals of active power output behaviour:

1. **power gain** This interval starts from the point in time of detection of the event (Δfrequency, df/dt, frequency point, etc.) until a pre-defined value, whether it is an agreed change in active power ΔP, 90% of the agreed change in active power P (as shown in Figure 22), a defined time limit or a defined frequency, etc.
2. **steady state:** This interval runs between the end of the power gain interval until a defined value such as a time interval limit, a defined frequency level or change has been reached, etc.
3. **ramp-down:** This interval starts from the end of the steady state interval until a defined value has been reached such as the available active power output, the pre-event power output or a defined time limit, etc.
4. **recovery:** Interval from the end of the ramp-down interval until a defined value has been reached such as a time limit. This interval essentially covers the time taken for the DUT to stabilize.

Data recording and measurement accuracy shall follow the specification in chapter 7.5.4

8.3.4.4 Documentation

The following parameters shall be calculated and documented in a test report:

- Setting of synthetic inertia control parameters according to
- Table 10

Table 10 – synthetic inertia settings

Parameter	Set value
Default active power gain ΔP (p.u.)	
Gradient of active power boost dP/dt (rising) in kW/s (p.u./s)	
Gradient of active power boost dP/dt (falling) in kW/s (p.u./s)	
$f_{\text{inertia, trigger}}$ in Hz	
$f_{\text{inertia, recovery}}$ in Hz	

Time-series of:

- Measured positive sequence active power output at the grid connection point
- Measured rotational speed of the DUT at the rotor shaft
- Measured frequency or the frequency reference value f_{sim}, measured as 0,1 s average value at the grid connection point.
- Available active power provided by the WT controller

For 5 s prior to the start of the synthetic inertia event and at least 5 s after the active power recovery phase of the DUT has terminated.

Calculated parameters according to Table 11

Table 11 - Synthetic Inertia results

Period of measurements						
Operational mode of the DUT during the test						
Active power range resp. wind speed range	**0,3 P_n**	**0,5 P_n**	0,8 P_n	1,0 P_n	$v > v_n$ Constant wind speed	$v > v_n$ Variating wind speed
Test number	**1**	**2**	**3**	**4**	**5**	**6**
Pre-event: steady state average output power in p.u.						
Pre-event: steady state maximum output power in p.u.						
Pre-event steady state minimum output power in p.u.						
Response time in ms						
Settling time in ms						
Steady-state time in ms						
Ramp-down time in ms						
Recovery time in ms						
Recovery period minimum power in p.u.						
Recovery period average output power in p.u.						

A report template is given in Annex A.

8.3.4.5 Transferability of test results

The test results provide an overview of the control performance in relation to fast frequency changes / events.

The test results can replace full-scale wind turbine measurements of the synthetic Inertia response.

8.3.5 Reactive power control

8.3.5.1 Description

The aim of this test is to determine the reactive power control response of the DUT to reference commands. The control behavior will be determined in relation to the static error, the rise time and the settling time of reactive power using either reactive power, voltage or cos φ reference values, depending on the wind turbine control system as specified by the manufacturer.

8.3.5.2 Test setup & test conditions

The measurement shall at least be performed on a category 2b test bench as described in chapter 7.

The DUT shall include at least the components and control functions as defined in Annex B.2.

Different from the general requirement above, for type IV wind turbines, the test can be performed without generator, on a category 3a test bench.

8.3.5.3 Test & measurement procedure

The test procedure as described in IEC 61400-21-1 section 8.4.6.1 for the steady state and dynamic response test shall be applied.

8.3.5.4 Documentation

The variables given in IEC 61400-21-1: 2019 section 8.4.6.3 shall be calculated.

The data, tables and figures given in IEC 61400-21-1 section 8.4.6.3 and Annex A shall be documented.

8.3.5.5 Transferability of test results

The test results can replace full-scale wind turbine measurements of the reactive power control performance.

The reactive power demand of the transformer and cables can be added by calculations to the final result, based on the data and measurement reports of these components.

8.4 Voltage fault ride through

8.4.1.1 General

The following chapter describes the test procedures according to:

- Strategy 1: Performance tests at nacelle level

- Strategy 2: Functionality and capability tests on subsystem and/or component level

As e.g. shown in Figure 2.

In subchapter 8.4.2, strategy 1 is taken up, in which FRT tests are typically described at nacelle level, which can be used directly, taking a transferability assessment into account, instead of a field test. If validated results can be shown on test benches of other classes (e.g., test bench category 2a), it is also possible to perform the performance test on this test benches (see chapter 5).

In subchapter 8.4.3, strategy 2 is taken up, which considers the idea of the division into functionality and capability tests. In combination with performance tests or field tests, an assessment of the ability to ride through undervoltage and overvoltage events in the grid and support it according to the requirements is possible.

Field tests cover the full scope of FRT testing. Performance testing also covers the full scope of testing and can be equated with detailed documentation of the missing components on the test benches including an associated risk assessment for the transferability assessment of results.

Capability tests and functionality tests can replace certain tests. Some test examples are described in subchapter 8.4.3. A combination of capability tests, functionality test and performance tests can reduce the test effort on the test bench for performance testing or in the field. These tests can be performed on different test benches and within different stages of WT development process. The results are combined at the end and proven by individual performance tests or field tests.

8.4.2 FRT - Performance testing according to Strategy 1

The following objective is to describe the proof for riding through grid faults and to validate the performance of dynamic grid support. Undervoltage events and overvoltage events are described in subchapter 8.4.2.1 and subchapter 8.4.2.3. Due to the capabilities of modern grid emulators not only to adjust voltages and frequencies according to the specifications, but also to emulate a grid impedance in the controlled mode of operation, there are two described variants of the test execution.

Variant 1 describes the tests with definitions of IEC 61400-21-1 with regard to the voltage requirements.

Variant 2 describes the tests with the definitions of IEC 61400-21-1 with regard to the voltage requirements and also concretizes the requirements on the dynamic grid impedance changes, from a grid emulator.

The chapters have a uniform structure starting with a very brief introduction; the description of the test setup and description of the components to be emulated; the actual description and definition of the tests; the measurement data to be recorded for the purpose of documentation; and the explicit identification of special features of the respective test execution, so that a final classification and evaluation of the tests can be carried out.

8.4.2.1 Fault ride through without impedance control (Variant 1)

8.4.2.2 Description

The following chapter describes the test setup and test methodology for demonstrating the overvoltage and undervoltage performance of a DUT with a specified voltage shape according to IEC 61400-21-1 without dynamic impedance control.

8.4.2.2.1 Test setup & test conditions

To perform the FRT tests, requirements are specified for the DUT and the test bench, which are needed to prove the FRT performance of the DUT.

Overview of components, subsystems and control functions for FRT performance tests

Type of Test	Chapter	test bench system	Functionality test	Capability test	Performance test	Converter System (Component)	Generator (Component)	Additional Cap- banks (Component)	Filter (Component)	Grid Power Control (active Power) (Function)	Grid Power Control (reactive Power) (Function)	Generator Power Control (or speed controlor / torque control) (Function)	Switch Gear (Circuit breaker / Contactor) (Component)	Transformer (Component)	Aux- equip. (Component)	Grid (FRT) Current Control (Function)	Grid Voltage Control (Function)	Frequency Control (Function)	Grid protection funtions (Function)	Hub (Component)	Blades (always emulated) (Component)	Pitch system (Component)	Pitch controller (Function)	Drive train (incl. Gearbox) (Component)
UVRT	8.4.2	1a	x	x	x	x	x	x	x	x	x	x	x^2	x	x	x	x	3	4	x^1	x^1	x^1	x^1	x^1
OVRT	8.4.2	1a	x	x	x	x	x	x	x	x	x	x	x^2	x	x	x	x	3	4	x^1	x^1	x^1	x^1	x^1

1 = can be either emulated or physical available
2 = if not physicaly at the test bench, the trigger signal sould be measured
3 =Not necessary if the manufacturer can declare that this function has no effect on the FRT.
4 = If the trigger signal for switch gear shell be recorded, the grid protection functions are needed

Figure 23 - Overview of DUT components for FRT-performance test

Figure 23 provides an overview of which components must be set up as a hardware component on the test bench and has to be emulated during the tests. Furthermore, a test bench system is selected.

The FRT-tests have to be performed on a category 1a test bench as describes in chapter 7 (Figure 6). Test can be done at other test bench classes with mHiL system if the validity of the measurements can be shown. The test bench must meet the following characteristics:

For type IV wind turbine, a quasi-stationary model for rotor emulation, as well as a laminar wind conditions, are sufficient. Hence, the rotor and structure emulation can correspond to level 2 of Table 3.

For type III wind turbine the rotor and structure emulation must correspond to level 1 of Table 3.

UVRT/OVRT HW equipment as described in chapter 7.5.3 is required to perform the FRT tests. Figure 24 is based on Figure 16 of IEC 61400-21-1: 2019 and describes the tolerance of the positive sequence voltage for an undervoltage event with disconnected DUT under test. It is stated as per unit of the pre fault voltage.

Annex D shows some examples of the transferability of the transient voltage transition between the field measurement and test bench measurement campaigns. Annex D also explains why the tolerance band for the dynamic range in Figure 16 of IEC 61400-21-1 is no longer available.

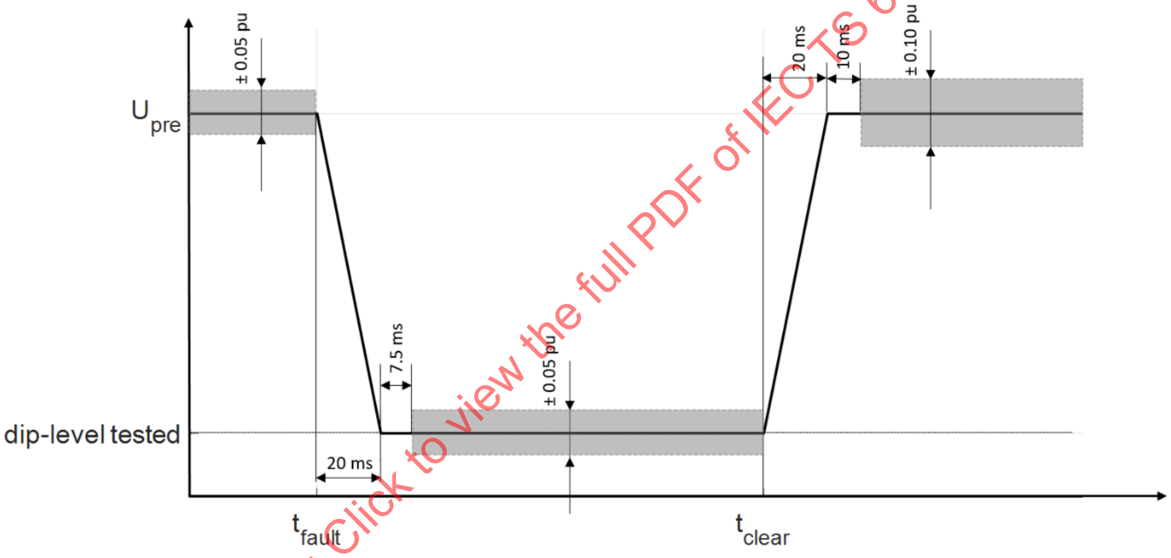


Figure 24 - Tolerance of the positive sequence voltage for the undervoltage event with disconnected DUT under test

Description of Figure 24:

- There are three areas, the pre-fault voltage, the fault case and the post-fault voltage
  - In the pre-fault range, the voltage may differ from the set point by ±0,05 p.u.
  - The most important value is the tested dip-level. Here again, a deviation of ±0,05 p.u. is possible.
  - After the fault, a deviation of ± 0,1 p.u. from the pre-fault value is permissible.
- The transition between the areas requires at least 20 ms in the positive sequence system.

   - There is a tolerance of total 7,5 ms for the positive sequence voltage during the dip. After this time, the positive sequence voltage needs to be within the tolerance band around the tested dip-level.
   - The tolerance on the positive sequence voltage during the recovery is 10 ms. After this time, the positive sequence voltage needs to be within the tolerance band around the post-fault voltage.
- The time from t_{fault} to t_{clear} describes the fault duration.
- Further requirements:
   - The transient voltage transition in the instantaneous phase voltage is linear, with a constant slope.
   - The dip starts at the same time in all affected phases.

Note: If the exact behavior of a voltage divider based test equipment should be represented the performance of real circuit breakers needs to be considered. That means during fault clearance, the voltage return for three-phase faults is performed via a two-phase fault.

8.4.2.2.2 Test & measurement procedure for UVRT-Tests

The number of tests and operational modes needs to be defined and describes by the manufacturer in order to document the capability of the DUT. It is recommended to test at four different undervoltage levels:

- minimum voltage the DUT can ride through U_{min},
- U_{min} + 0,2 p.u. of the under voltage range capability U_{UVRC},
- U_{min} + 0,5 p.u. U_{UVRC} and
- U_{min} + 0,75 p.u. U_{UVRC}.

Each dip should be repeated twice in a row.

The definition of the number of the voltage levels and the exact duration of the dips is given by the manufacturer capability chart as shown in Figure 25.

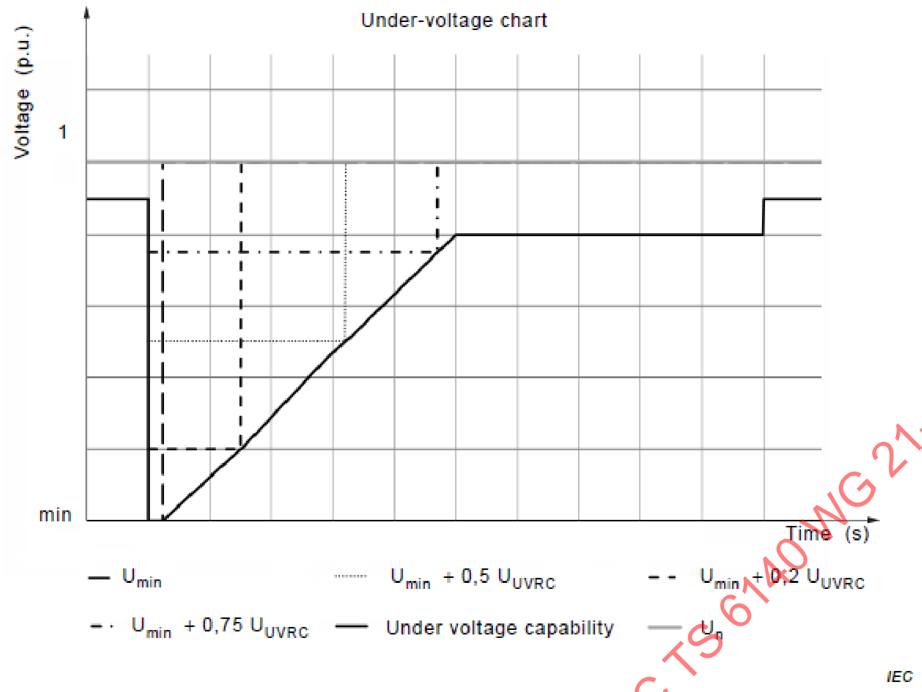


Figure 25 - Example of an undervoltage test chart

Table 12 in IEC 61400-21:2019 shows the specified magnitudes and durations for the undervoltage event occurring by doing a no-load test. The duration is defined according to the given capability curve. Figure 24 describes the tolerance of the no-load tests. In case of a grid emulator, chapter 8.4.2.2.1 specifies further test conditions.

The length of the time-series is defined as from stable conditions prior to the voltage dip or swell and until the effect of the undervoltage or overvoltage event has abated. Typically, 10 s prior and 10 s post fault.

Further, the test shall be carried out for the DUT operating at partial load, between 0,25 p.u. and 0,5 p.u. and under full load conditions, above 0,9 p.u. of the nominal active power.

8.4.2.2.3 Test & measurement procedure for OVRT-Tests

The number of tests and operational modes needs to be defined and describes by the manufacturer in order to document the capability of the DUT.

Each swell should be repeated twice in a row.

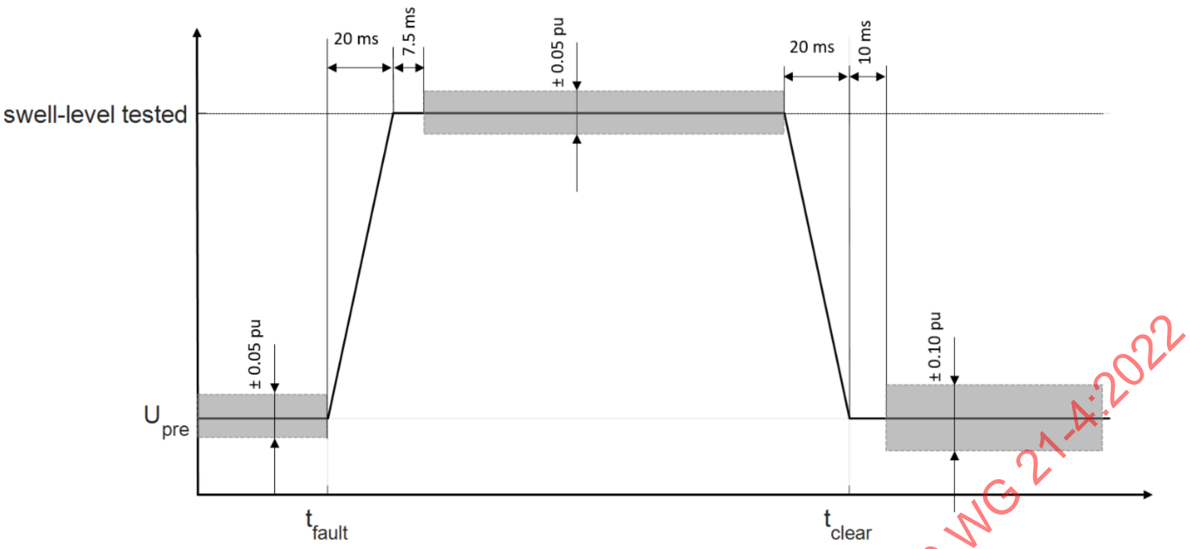


Figure 26 - Tolerance of the positive sequence voltage for the overvoltage event with disconnected DUT

The definition of the number of the voltage levels and the exact duration of the swell is given by the manufacturer capability chart as shown in Figure 27.

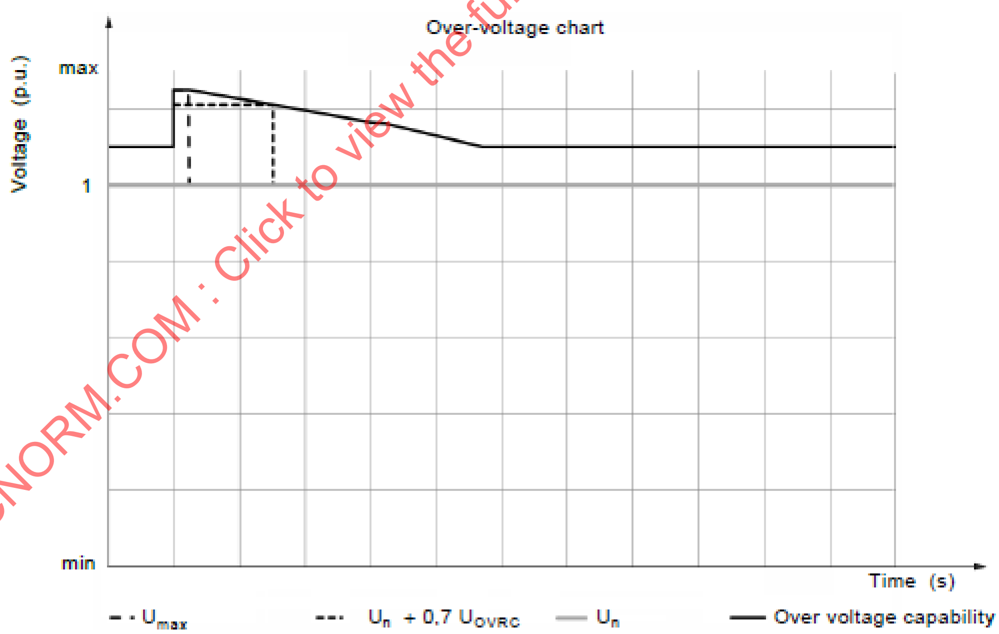


Figure 27 - Example of an over voltage capability chart

Table 13 in IEC 61400-21-1:2019 shows the specified magnitudes and durations for the overvoltage event occurring by doing a no-load test. Figure 26 describes the tolerance of the no-load tests. The duration is defined according to the given capability curve. In case of a grid emulator, chapter 8.4.2.2.1 specifies further test conditions.

The test shall be carried out for the WT operating at partial load, between 0,25 p.u. and 0,5 p.u. and under full load conditions, above 0,9 p.u. of the nominal active power.

It is recommended to conduct and evaluate no-load tests before performing measurements with converter-based test equipment. Check whether the required dynamic is maintained during voltage dip and voltage recovery. Furthermore, the resulting voltage level and the phase angle of the voltage during the dip must be verified and documented. The specified setpoint must also be stated.

8.4.2.2.4 Documentation

The following information shall be given and documented:

- Description of the test setup / Real time simulator setup
- Description of the impedance of the test bench system and the passive components of the DUT
- Signals for validation of rotor emulation, for example emulated wind speed, emulated torque, Torque measures
- Adjusted parameters at the grid emulator for the voltage dip and the voltage recovery

The following parameters and measurements must be documented for the DUT:

- positive and negative sequence voltage,
- positive and negative sequence currents,
- active power,
- reactive power,
- active current,
- reactive current,
- simulated wind speed or available power
- phase angles
- set points for active and reactive power

The positive sequence and negative sequence values shall be calculated in accordance with Annex C of IEC61400-21-1:2019.

All measurements per unit are referred to the nominal values. Further the calculation of the trigger point of fault start must be document.

8.4.2.2.5 Transferability of test results

The results of performance testing can replace full-scale wind turbine measurements of UVRT and OVRT.

If the tests in the field and on the test bench are performed with the same test setup, no further considerations are necessary. If a different setup is used on the test bench, it must be described and further consideration is necessary as shown in Appendix C.

8.4.2.3 Fault ride through with impedance control

8.4.2.4 Description

To demonstrate the FRT capability of a DUT according to IEC 61400-21-1 on a subsystem or component level, the test bench has to emulate the test procedure like a voltage-divider based test equipment. This chapter is representing equivalent testing procedure according to voltage-divider based test equipment testing in field.

8.4.2.4.1 Test setup & test conditions

To perform the FRT tests, requirements are specified for the DUT and the test bench, which are needed to prove the FRT performance of the DUT.

Figure 23 provides an overview of which components must be set up as a hardware component on the test bench and has to be emulated during the tests. Furthermore, a test bench system is selected.

The FRT-tests have to be performed on a category 1a test bench as describes in chapter 7 (Figure 6). Test can be done at other test bench classes with mHiL system if the validity of the measurements can be shown. The test bench must meet the following characteristics:

For type IV wind turbine, a quasi-stationary model for rotor emulation, as well as a laminar wind conditions, are sufficient. Hence, the rotor and structure emulation can correspond to level 2 of Table 3.

For type III wind turbine the rotor and structure emulation must correspond to level 1 of Table 3.

UVRT/OVRT HW equipment as described in chapter 7.5.3 is required to perform the FRT tests.

Figure 24 is based on Figure 16 of IEC 61400-21-1: 2019 and describes the tolerance of the positive sequence voltage for an undervoltage event with disconnected DUT. It is stated as per unit of the pre fault voltage.

The requirements for full converter-based grid emulators with dynamic impedance control are described in the following.

Methodology of impedance control:

The impedance at the connection point of the WT changes dynamically during field tests with the voltage divider-based test equipment due to the connected and disconnected impedances. Figure 28 demonstrates the impedance profile at the connection point of the WT using the voltage divider-based test equipment.

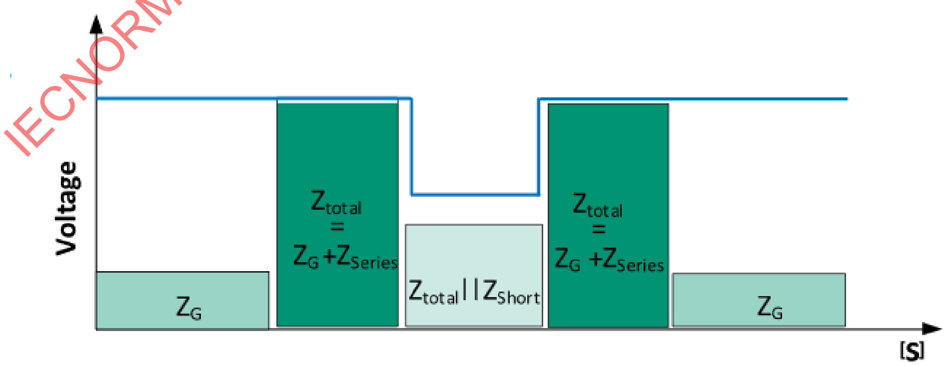


Figure 28 - FRT Impedance profile

Grid emulators provide the additional option of virtual impedance adjustment. This allows the voltage divider-based test method's behaviour to be reproduced on the test bench. For this purpose, not only the voltage magnitude and phase are adjusted during the tests, but also the emulated grid impedance.

Note: The behaviour of the voltage divider-based test device can be reproduced by a complete reproduction of the impedance curve, including all dynamic changes. Another way to consider the different resulting impedances in the fault case is to set the fault impedance $Z_{total} \| Z_{short}$ once at the beginning of the test series. This eliminates the need to dynamically adjust the impedance during the test. Nevertheless, various grid short-circuit powers depending on the fault depth are taken into account using this approach.

Annex D shows some examples of the transferability of the transient voltage transition between the field measurement and test bench measurement campaigns.

8.4.2.4.2 Test & measurement procedure for UVRT-Tests

The test procedure is the same as described in subchapter 8.4.2.2.2.

8.4.2.4.3 Test & measurement procedure for OVRT-Tests

The test procedure is the same as described in subchapter 8.4.2.2.3.

8.4.2.4.4 Documentation

It is recommended to conduct and evaluate no-load tests before performing measurements with converter-based test equipment. Check whether the required dynamic is maintained during voltage dip and voltage recovery. Furthermore, the resulting voltage level and the phase angle of the voltage during the dip must be verified and documented. The specified setpoint must also be stated.

The documentation is the same as described in subchapter 8.4.2.2.4.

Additional documentation of parameters and measurements for the test bench:

- Emulated impedance

8.4.2.4.5 Transferability of test results

The transferability procedure is the same as described in subchapter 8.4.2.2.5

8.4.3 Functionality and Capability testing according to Strategy 2

In chapter 6 a general classification and naming of components is made. Reference is then made to the tables in Appendix B.2, which show that UVRT and OVRT tests can be divided into the following three classifications:

a) Functionality tests

b) Capability tests

c) Performance tests

The tests of class a) and b) will now be discussed in more detail below.

8.4.3.1 Definition of the DUT

In general, from the list of components in the tables in Annex B.2, the component must be determined by e.g. the manufacturer, which are suitable for the functionality or capability tests described here. This can be assessed differently depending on the wind turbine design.

For the basic description of the procedure in the following subchapters, the components were selected as follows:

- Controller for functionality tests
- Converter for capability tests

The focus is of course on UVRT and OVRT tests.

It is not further specified whether it is the converter or the wind turbine controller. The decisive factor is in which controller the corresponding functionalities are implemented.

The following components from Figure 4 are discussed here:

- WT control system
- FRT control
- Convert system + filter system (the filter was also included, as it may be an integrated part of the converter. This can vary depending on the manufacturer.)

It should also be mentioned again that the controller level represents the lowest testing level and only functionality tests can be carried out on this level and no e.g. capability tests.

However, one level higher (e.g. converter level) functionality and capability tests can be carried out. Figure 29 provides an overview of the components on which functional tests can be performed.

Overview of components, subsystems and control functions for GFRT functionality tests																								
						Component	Component	Component	Component	Function	Function	Function	Component	Component	Component	Function	Function	Function	Function	Component	Component	Component	Function	Component
Type of Test	Chapter	test bench system	Functionality test	Capability test	Performance test	Converter System	Generator	Additional Cap- banks	Filter	*Grid Power Control (active Power)*	*Grid Power Control (reactive Power)*	*Generator Power Control (or speed controlor / torque control)*	Switch Gear (Circuit breaker / Contactor)	Transformer	Aux- equip.	*Grid Current Control*	*Grid Voltage Control*	*Frequency Control*	Grid protection funtions	Hub	Blades (always emulated)	Pitch system	*Pitch controller*	Drive train (Incl. Gearbox)
UVRT	8.4.3	3c	X							x	x	x				x	x	3						
OVRT	8.4.3	3c	X							x	x	x				x	x	3						

3 = not necessary if the manufacturer can declare that this function has no effect on the FRT.

Figure 29 - Overview components for FRT functional tests

Figure 30 provides an overview of the components on which capability tests can be performed.

Overview of components, subsystems and control functions for GFRT capability tests

						Component	Component	Component	Component	Function	Function	Function	Component	Component	Component	Function	Function	Function	Function	Component	Component	Component	Function	Component
Type of Test	Chapter	test bench system	Functionality test	Capability test	Performance test	Converter System	Generator	Additional Cap- banks	Filter	*Grid Power Control (active Power)*	*Grid Power Control (reactive Power)*	*Generator Power Control (or speed controlor / torque control)*	Switch Gear (Circuit breaker / Contactor)	Transformer	Aux- equip.	*Grid Current Control*	*Grid Voltage Control*	*Frequency Control*	Grid protection funtions	Hub	Blades (always emulated)	Pitch system	*Pitch controller*	Drive train (Incl. Gearbox)
UVRT	8.4.3	3a		x		x	x[5]		x	x	x	x				x	x	[3]	[4]	x[1]	x[1]	x[1]	x[1]	x[1]
OVRT	8.4.3	3a		x		x	x[5]		x	x	x	x				x	x	[3]	[4]	x[1]	x[1]	x[1]	x[1]	x[1]

[1] = can be either emulated or physical available
[3] =Not necessary if the manufacturer can declare that this function has no effect on the FRT.
[4]= If the trigger signal for switch gear shell be recorded, the grid protection functions are needed
[5]= can be emulated for Type IV turbines, if the manfucturer can show validation results

Figure 30 - Overview components for FRT capability tests

8.4.3.2 Functionality testing

8.4.3.2.1 Introduction

The terminology functionality in relation to UVRT and OVRT tests is addressing controller (software) functions and consequently some form of controller testing.

The following functionalities are examples that are of greater importance in order to meet grid requirements. Other functionalities are conceivable and can also be tested based on the procedure described here.

Example of functionalities:

- Detection of FRT
- Deadband of current support
- K-factor
- Prioritization of contribute with reactive or/and active current
- Controlling of positive and negative symmetrical system (each phase)
- Controlling of the active power ramp rate (P_ramp_rate) post fault
- Handling of eventually a frequency shift due to a phase jump

In order to ensure a common understanding of the nature of such functionalities, the above listed functions are explained in more detail in Annex F.

8.4.3.2.2 Test setup & test conditions

The measurement shall at least be performed on a category 3c test bench as described in chapter 7.

The DUT shall include at least the components and control functions as defined in Annex B.2.

8.4.3.2.3 Test & measurement procedure

In general, the functionality tests should complement the capability and performance tests (see Figure 2. The test plan and its test parameters need to be developed individually.

In principle, the tests could be carried out as described in chapter 8.4.2.2.2 and 8.4.2.2.3, respectively and in IEC 61400-21-1:2019 section 8.5 and possibly supplemented by further tests, depending on the functionalities to be verified.

The number of tests and operational modes need to be defined and described by the manufacturer in order to document the functionality.

Preconditions:

- The mode and therefore the control parameter need to be send to the DUT
- The parameter (voltage and frequency) of the emulated grid is set to nominal values
- All emulations and hardware dummies need to be in operation

Test procedure:

- The DUT needs to be start up to a steady state operation point (e.g. 100% active power)
- Start of measurement
- After a certain time (e.g. 5 sec) the desired UVRT or OVRT event (box e in Figure 14) is triggered
- After the fault (e.g. 5 sec.) the measurement can be stopped

8.4.3.2.4 Documentation

The following must at least be documented:

- Description of the entire test bench
- Description of the DUT
- Description of the functionality to be checked
- Description of the measurement data recording (measurement system, sampling times, etc.)
- Representation of the input and output signals as a time plot
- Possibly further representations, which are necessary to show the functionality

8.4.3.3 Capability testing

8.4.3.3.1 Introduction

Capability testing in relation to FRT tests can be carried out at converter hardware level.

The following capabilities are examples, which were of greater importance in the past to meet grid requirements. Further capabilities are conceivable and can be tested based on the procedure described here.

Example of capabilities:

- Run through, e.g. without disconnection
- Operate the max. capability curve, e.g. to support with reactive current

- Shows the correct post fault behaviour
- Converter – UPS works (if available)
- Run through
- Side Components for the converter like (e.g. UPS, Crowbar, Chopper, etc. support as needed)
- Operate multi faults
- Handling of dynamic side aspects (e.g. phase jumps, impedance jumps, inrush effects, etc.)
- Operate the specified grid frequency 50Hz or/and 60Hz

8.4.3.3.2 Test setup & test conditions

The measurement shall at least be performed on a category 3a test bench as described in chapter 7.

The DUT shall include at least the components and control functions as defined in Annex B.2.

8.4.3.3.3 Test & measurement procedure

The tests can be performed as describes in subchapter 8.4.2.4.2 and subchapter 8.4.2.4.3. The operation modes must be specified and described by the manufacturer in order to document the capability.

8.4.3.3.4 Documentation

The following must at least be documented:

- Description of the entire test bench
- Description of the DUT
- Description of the capability to be checked
- Description of the measurement data recording (measurement system, sampling times, etc.)
- Representation of the input and output signals as a time plot
- Possibly further representations, which are necessary to show the functionality

8.4.3.4 Performance testing according to strategy 2

To complete the FRT testing according to strategy 2 (cf. Figure 2), the functionality and capability testing described before are complemented by a performance test. This performance test includes only worst-case scenarios, which verify the dynamic behaviour of the DUT. Performance tests can be carried out at type 1a test benches or in the field. This performance test can be done at other test bench classes with mHiL system if the validity of the measurements can be shown.

The worst-case scenario must be defined by the manufacturer.

8.4.3.5 Transferability of combined test results to field level

Since there is limited experience on combining different classifications of test cases on different system levels for grid compliance testing, this sections is of theoretical nature. More specific description through practical experience is required in the future.

The aspects discussed in more detail in the following paragraphs should already be mentioned today.

1. Transparent, continuous documentation of the entire process

   The entire process that is carried out by the manufacturer with regard to strategy 2 must be described transparently and in detail. This includes the listing of the systems and / or components and the test bench used in each case. The DUT (hardware and software) and its parameters as well as any emulations used for components that were not actually tested (e.g. pitch system, rotor, etc.) must be documented in detail. The description of the framework conditions of the simulated electrical network and, if the performance test takes place in the field test, the real network data to compare them are also important. The validation of the emulations with the real measurements must be shown and assessed.

2. Validation of maximum capability according to the manufacturer specification

   The entire process should demonstrate the electrical performance specified by the manufacturer. This means that it must at least be shown on the basis of appropriate tests that the maximum capability curve can be handled as expected and that the auxiliary systems such as (e.g. UPS for the converter controller, crowbar protection, chopper system, self-protection system, etc.) are working correctly and do not lead to the overall system tripping. In addition, it must be checked whether the expected electrical behaviour, such as voltage support through reactive current feed, occurs in accordance with the parameter settings in the DUT or whether, for example, overvoltage’s do lead to destruction and thus failure.

   In addition, this method offers a more detailed examination of performances such as the behavior in extreme network conditions, for example with regard to the network short-circuit power or the examination of different nominal network frequencies of the voltage.

3. Proof of functionalities

   One means of reducing the performance test is to carry out functionality tests as described in Chapter 8.4.3 on a lower component level. This must be specifically described by the manufacturer in the overall context of how these are combined with the capability and / or performance test. It makes sense for the manufacturer to carry out worst case scans as a performance test and combine this with the functionality tests.

4. Validation of applied hardware emulations within this procedure

   It is possible to emulate hardware for this process. The overall concept of these individual procedures must consider that these emulations are valid. Corresponding UVRT or OVRT tests, e.g. field tests, must show the correct dynamic behaviour of the rotor system in relation to the emulation. In general, it must be shown that the emulations are comparable with the real behaviour within a certain tolerance band.

5. Risk analysis

   The method offers new possibilities in the future to sufficiently prove the requirements for the wind turbines (e.g. considering more extensive the corresponding frequency system (50Hz/60Hz), phase jumps and/or impedance changes during FRT, different grid short-circuit power, etc.). It is only now possible to test certain extreme points that could not be tested in the past. However, it must be avoided that there are increased risks that incorrect behavior due to systematic design errors is no longer recognized. For this purpose, the manufacturer must create a risk analysis that describes in detail which risks his chosen concept could contain, to show this incorrect behavior no longer or strongly falsified.

6. Uncertainty analysis

   In addition to the risk analysis, an indication of the uncertainties of the important result parameters, such as reactive current delivery, power ramps on return of voltage, etc., when using test bench measurements compared to field measurements, must also be given.

8.5 Disconnection from the grid

This chapter describes the measurement and test procedures to prove the correct operation of the different grid protection systems in the DUT as well as the reconnection procedures.

8.5.1 Grid protection

8.5.1.1 Description

The purpose of grid protection is to disconnect the DUT from the grid during abnormal voltage or frequency conditions.

The aim of these tests is to prove the correct operation of this protection, as defined in IEC 61400-21-1.

8.5.1.2 Test setup & conditions

The test shall at least be performed on a category 3c test bench test setup according to chapter 7.

The DUT shall include at least the components and control functions as defined in Annex B.2.

The test can be performed on the subsystem level (if the grid protection is realised by a separate unit, like a separate grid protection relay) or on a hardware in the loop test of the grid protection system of the DUT, as described in IEC 61400-21-1: 2019 section 8.6.2.1

The protective system under test including voltage transformers, grid measuring device, trip circuit and main circuit breaker shall be of identical type to that applied in the corresponding WT type.

The protection test set, including transformer, used for secondary injection of voltage and frequency changes shall fulfil the accuracies as described IEC 61400-21-1 or defined in IEC 60255-181 and IEC 60255-127.

The trip signal from the grid protection system shall be connected as an input to the protection test set in order to prove the pick-up value as well as to measure the time delay.

8.5.1.3 Test procedure

The scope of these tests as well as the test procedure are defined in the IEC 61400-21-1 sections 8.6.2.2 and 8.6.2.3. and shall be applied to the DUT.

8.5.1.4 Documentation

The applied settings as well as the results of these tests shall be documented as defined in IEC 61400-21-1 section 8.6.2.4 and IEC 61400-21-1 Annex A.

If a separate measurement system is used, it is recommended to record the following channels:

- Voltages at the DUT terminals
- frequency at the DUT terminals

- trip signal of the DUT
- digital or analogue signal showing point in time of frequency change (output from protection test set)
- main circuit breaker auxiliary contact (if used for full trip test).

In addition the following shall be documented as shown in Table 12, a report template is given in Annex A.

Table 12 - Documentation requirements for grid protection test

Grid protection system	Manufacturer:	
	Type:	
	Serial number:	
	Software version:	
Voltage transformers	Manufacturer:	
	Type:	
	Serial numbers:	
	Location of measurement point (high side/low side of PGU step-up transformer):	
	Primary voltage:	
	Ratio:	
Main circuit breaker	Manufacturer:	
	Type:	
	Serial number:	

8.5.1.5 Transferability of test results

The test results can replace full-scale wind turbine measurements.

8.5.2 RoCoF protection

8.5.2.1 Description

The DUT behaviour during grid events that cause a fast change of frequency in a short time frame shall be tested. The DUT protection shall trip when an excessive rate of change of frequency (RoCoF) is encountered. The aim of these tests is to prove the correct operation of this protection, as defined in IEC 61400-21-1.

8.5.2.2 Test setup & test conditions

The test shall at least be performed on a category 3c test bench test setup according to chapter 7.

The DUT shall include at least the components and control functions as defined in Annex B.2.

The protective system under test including voltage transformers, grid measuring device, trip circuit and main circuit breaker shall be of identical type to that applied in the corresponding WT type.

8.5.2.3 Test setup & procedure

The protection test system, including transformer, used for secondary injection shall fulfil the accuracies as described IEC 61400-21-1 or defined in IEC 60255-181.

The trip signal from the grid protection system shall be connected as an input to the protection test system in order to prove the protection settings and to measure the protection time delay.

The scope of these tests as well as the test procedure are defined in the IEC 61400-21-1:2019 section 8.6.3.2. and shall be applied to the DUT.

8.5.2.4 Documentation

The applied settings as well as the results of these tests shall be documented as defined in IEC 61400-21-1:2019 section 8.6.3.3 and IEC 61400-21-1 Annex A.

If a separate measurement system is used, it is recommended to record the following parameter:

- Voltages at the DUT terminals
- frequency at the DUT terminals
- trip signal of the DUT
- digital or analogue signal showing point in time of frequency change (output from protection test set)
- main circuit breaker auxiliary contact (if used for full trip test)

In addition the following shall be documented as shown in Table 13, a report template is given in Annex A.

Table 13 - Documentation requirements for RoCoF test

Grid protection system	Manufacturer:	
	Type:	
	Serial number:	
	Software version:	
Voltage transformers	Manufacturer:	
	Type:	

	Serial numbers:	
	Location of measurement point (high side/low side of PGU step-up transformer):	
	Primary voltage:	
	Ratio:	
Main circuit breaker	Manufacturer:	
	Type:	
	Serial number:	

8.5.2.5 Transferability of test results

The test results can replace full-scale wind turbine measurements.

8.5.3 Reconnection time

The aim of the reconnection time test is to show that the turbine automatically reconnects after a grid outage of up to 10 minutes after which the power is ramped up following a predefined ramp rate.

Due to the large number of UPSs and auxiliary systems (e.g. pitch motors) involved here and the resulting low transferability of these test results, this test shall only be carried out with the complete WT in operation.

9 Additional measurement and test of electrical characteristics under controllable test conditions

This chapter defines additional tests, which are only possible in a controlled test bench setup as described in this TS in relation to power quality, steady state operation, dynamic response and control performance, as well as the documentation requirements and a guidance for the transferability of the test results towards the WT.

9.1 Power quality aspects

9.1.1 Flicker Control

9.1.1.1 Description

This chapter gives guidance for testing of flicker mitigation due to control issues at a test bench. These tests are optional. The aim of the measurement is to determine the voltage flicker during continuous operation at the terminals of the DUT.

The test results are shown for short term P_{st} values, but are also be valid for long term P_{lt} values.

9.1.1.2 Test setup & test conditions

The measurement shall at least be performed on a category 1b test bench as described in chapter 7.

The DUT shall include at least the components and control functions as defined in Annex B.2

For these tests a grid emulator is recommended. In order to obtain more realistic view of the DUT flicker emission, it is recommended that the DUT sees the emulated voltage fluctuations behind an impedance Z = R + jX.

The following possibilities are proposed:

a) Use of a Variable Voltage – Emulated Impedance (Z) Grid Emulator Figure 31.

b) Use a constant voltage and impedance Grid Emulator and add the variable series impedance Z and a controllable fluctuating shunt load, ohmic or inductive Figure 32

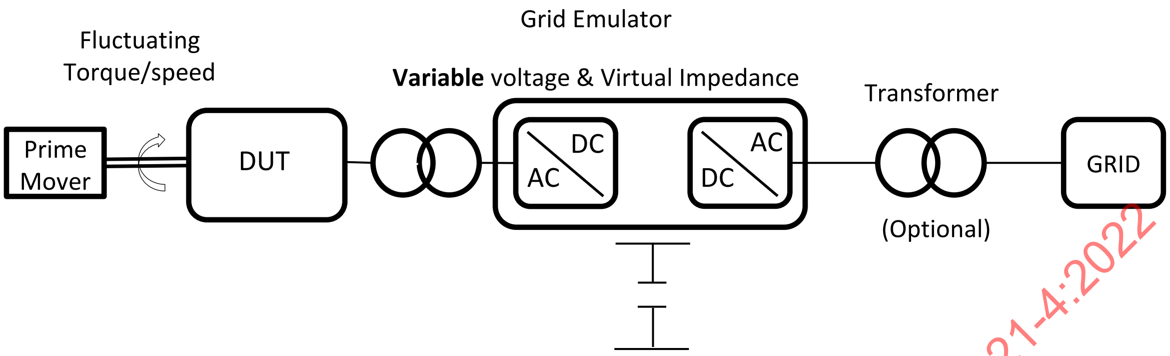


Figure 31 - Variable voltage and impedance grid emulator (case a)

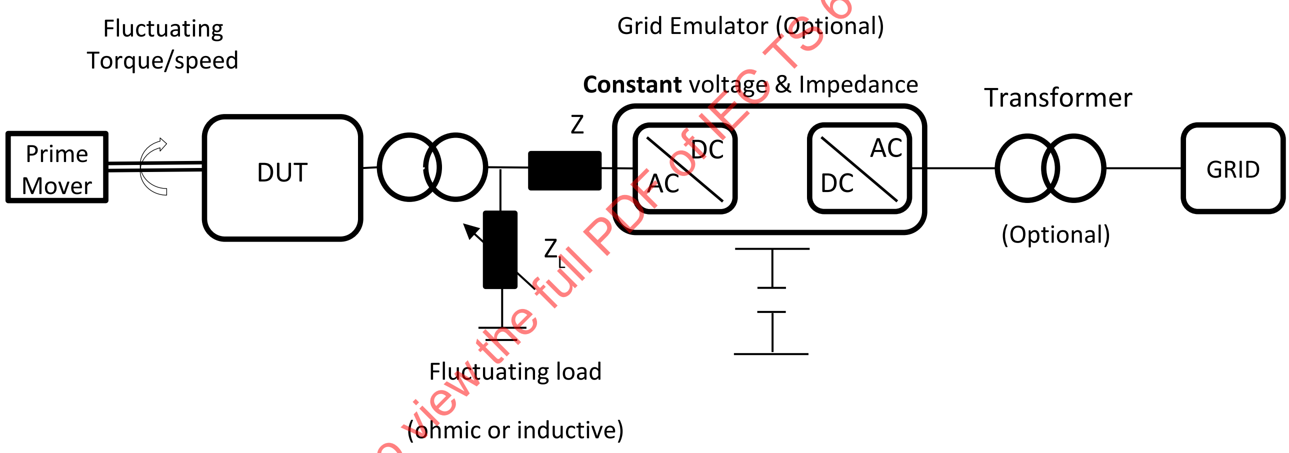


Figure 32 - Constant voltage and impedance grid emulator with controllable load

(case b)

The magnitude of the impedance Z including the impedance of the grid emulator (and of the grid) for cases a) and b) should be in the range giving adequate Pst values. The impedance phase angles ψk (ψk=arctan(X/R) must be ψ_k = 30°, 50°, 70˚ and 85˚ with a tolerance of ±5°, where R is the resistive and X the inductive component of the total impedance.

For case b), Figure 32, the grid emulator may be omitted, so that the impedance Z is directly connected to the grid.

9.1.1.3 Test & measurement procedure

The following tests for the flicker mitigation due to control issues shall be performed:

It is recommended that the test setup a) or b) generates predefined voltage fluctuations at the DUT with frequencies of:

- 0,5 Hz
- 1.5 Hz
- 3.5 Hz
- 8.8 Hz

The DUT shall be in voltage control mode and compensates the voltage fluctuations by control of reactive power.

The power output of the DUT shall be 30% to 50% of P_n for partial load and 90% to 100% of P_n for full load testing.

For each test case, one test with constant and one test with fluctuating power output shall be performed.

The voltage flicker P_{st} as 10-minute values without and with the DUT at the terminal of the DUT shall be measured and compared with each other

Table 14 - Range of input relative voltage fluctuation $\Delta U/U_n$ for P_{st} output range about 0,2 and 0,5 for U_n = 230 V

Frequency	**Sinusoidal fluctuations**	**Rectangular fluctuations**
f [Hz]	dU/U [%]	dU/U [%]
0,5	0,67 – 1,69	0,16 – 0,41
1,5	0,30 – 0,76	
3,5		0,10 – 0,24
8,8	0,07 – 0,18	0,06 – 0,14

9.1.1.4 Documentation

A. Show results of voltage flicker severity index (P_{st}) with and without the DUT

Presentation of the results in a table as a function of different impedances and frequencies of voltage fluctuations, e.g.

Table 15 - Flicker P_{st} per power range and fluctuation frequency

Impedance angle		30°		50°		70°		85°	
Impedance	R								
	X								
Load in % of P_n	Frequency in Hz	Without DUT	With DUT	Without DUT	With DUT	Without DUT	With DUT	Without DUT	With DUT
Partial load (30% to 50% of Pn)	0,5 Hz								
	1,5 Hz								
	3,5 Hz								

	8,8 Hz								
Full load (90% to 100% of Pn)	0,5 Hz								
	1,5 Hz								
	3,5 Hz								
	8,8 Hz								
Maximum									
Period of measurements									
Operational mode (reactive control *Q*=0 / others)									

A report template is given in Annex A.

B. Flicker mitigation factor (ratio F=$P_{st\_with\_DUT}$/$P_{st\_without\_DUT}$)

Presentation of the results in a table as a function of different impedances and frequencies of voltage fluctuations, e.g.

Table 16 - Flicker mitigation factor (F) per power range and fluctuation frequency

Impedance angle		30°	50°	70°	85°
Load in % of P_n	Frequency in Hz	Flicker mitigation factor (ratio F=Pst_with_DUT/Pst_without_DUT)			
Partial load (30% to 50% of P_n)	0,5 Hz				
	1,5 Hz				
	3,5 Hz				
	8,8 Hz				
Full load (90% to 100% of P_n)	0,5 Hz				
	1,5 Hz				
	3,5 Hz				
	8,8 Hz				
Maximum					

A report template is given in Annex A.

9.1.1.5 Transferability of test results

The test results are supplementary to the full-scale wind turbine flicker measurements.

9.1.2 Flicker and voltage change during switching operations

9.1.2.1 Description

This chapter is to give guidance for testing of flicker and voltage change due to switching at a test bench. These tests are optional and can be performed in case the converter of the DUT is changed.

Note: Similar to the testing of flicker during continuous operation, for testing the effect of the switching operations of a wind turbine sufficiently, it shall be tested in the free field, so that the influence of the aerodynamic part is thoroughly incorporated (see the note for flicker during continuous operation).

9.1.2.2 Test setup & test conditions

The measurement shall at least be performed on a category 2b test bench as described in chapter 7.

The DUT shall include at least the components and control functions as defined in Annex B.2

For the connection of the DUT either a grid emulator or the public grid can be used.

9.1.2.3 Test & measurement procedure

The characteristics shall be stated for the following types of switching operations:

a) One start-up of the DUT at power of 10% of P_n shall be performed

b) One start-up of the DUT at nominal power P_n shall be performed

For each of the above types of switching operations, the values of flicker step factor $k_f(\psi_k)$ and voltage change factor for the network impedance phase angles ψ_k = 30°, 50°, 70° and 85° shall be stated, as defined in IEC 61400-21-1.

To determine the voltage change factor $k_u(\psi_k)$, and the flicker step factor $k_f(\psi_k)$, the maximum of the three phases for each type of switching operation shall be calculated.

NOTE 1 Further information on the measurement procedure for voltage changes and flicker during switching operations can be found in IEC 61400-21-1, chapters 8.2.2.2, 8.2.3, B.2, B.4.2 and B.4.3.

9.1.2.4 Documentation

The following parameters have to be reported as a function of the impedance phase angle, for each measured case:

- Flicker step factor
- Voltage change factor

It can be documented for example in a Table as described in Annex A.

Furthermore, time series of the voltage, current, active and reactive power shall be documented in graphs for both switching events.

9.1.2.5 Transferability of test results

The test results are supplementary to the full-scale wind turbine measurements of switching operations

9.1.3 Active filter / sink for harmonics

9.1.3.1 Description

Modern wind turbines can potentially actively improve the power system's quality of power. In case of resonance networks such as wind power plants, it is critical that the harmonic injection by wind turbines is very small and controlled.

Active filter functionality can be understood very broadly. Several technical solutions could be introduced in grid-connected converter functionality depending on the expected outcome, e.g. reduction of either harmonic current or voltage at the wind turbine terminal or at the remote bus. Among many others, the following active filtering functionalities could be, inter alia, specified:

- Local resonance damping: the aim of active filter is to mitigate or damp internal resonances within the wind turbine's internal circuit.
- Local harmonic current compensation: the task of active filter is to minimize the current flow between the wind turbine converter and the public grid.
- Local harmonic voltage distortion mitigation: the goal of active filter is to improve and minimize as much as possible the voltage distortion level at the converter terminals.
- Resonance damping at the remote bus: the wind turbines is programmed to damp prominent resonances in the wind power plant network leading to lower harmonic voltage distortion level.
- Harmonic compensation at the remote bus: the active filter in wind turbines leading to maintain the harmonic voltage distortion level at a selected bus bar.

Note: The purpose of this test is to carry out active filtering evaluation without knowing the exact control function being implemented.

9.1.3.2 Test setup & test conditions

The measurement shall at least be performed on a category 2b test bench as described in chapter 7.

The DUT shall include at least the components and control functions as defined in Annex B.2. Additional the components as specified for the harmonics evaluation in Annex E have to be taken into account for the active filter functionality test.

Grid emulator: The grid emulator shall be able to provide harmonic disturbances in the required frequency range and shall provide the harmonic contribution in open loop control, to avoid interactions with the harmonic control functionality of the DUT.

9.1.3.3 Test & measurement procedure

Harmonic background distortion measurement is required before the test is performed, to be able to evaluate the impact of the public grid on the test results.

Note: Please make sure that the harmonics of interest, e.g. the 5th, 7th, are measured at the DUT terminals, i.e. caused by the grid emulator, the public grid or the DUT itself.

The test shall be performed in two steps:

- **Step 1:** harmonic measurements at the DUT terminals before the active filter is activated
- **Step 2:** harmonic measurements at the DUT terminals after the active filter is activated.

Measurement procedure of active filtering functionality of the DUT:

- Set point reactive power: Q = 0 var.
  Optional: reactive power under- and overexcited at the maximum power bin.
- **Grid emulator:** Three, 10-minute data sets of instantaneous voltage and current measurements shall be collected for each 10% power bin (0% P_n – 100% P_n), and shall be performed with the same operational conditions as for the no load tests.
- **Public grid:** Seven, 10-minute data sets of instantaneous voltage and current measurements shall be collected for each 10% power bin (0% P_n – 100% P_n)
- The maximum value from the three or seven measurements of each power bin shall be taken.

Note: All three phases shall be measured at the same time during the measurements.

DUT: The following values shall be measured and reported in percentage of I_n and U_n respectively and for operation of the DUT within the active power bins 0, 10, 20, … 100% of P_n.

- Values of the individual current components
- Total current distortion up to the 50th harmonic order
- Values of the individual voltage components
- Total voltage distortion up to the 50th harmonic order

A synchronized to power system fundamental frequency rectangular 10-cycle window for 50 Hz and 12-cycle window for 60 Hz power systems is recommended for the analysis of measurements.

The DFT is applied to each of the measured currents and voltages with rectangular weightings. The active power shall be evaluated over the same time window as the harmonics.

9.1.3.4 Documentation

The tests results shall be reported in a table including measurements at the DUT terminals before the active filter (**Step 1**) and after the active filter (**Step 2**) is activated.

The emission of the magnitude voltage and current harmonics shall be documented in tables and graphs according to Annex A.

Public grid: The 95th percentile of current and voltage harmonics shall be measured and reported for public grid measurement.

Grid emulator: The max value of current and voltage harmonics shall be measured and reported for grid emulator measurement.

Table 17 - Active filtering (AF) evaluation table for voltage as current harmonics

Power bin / Harmonic order	**0%**		**10%**		**20%**		**…**		**100%**	
	w AF	w/o AF	w AF	w/o AF	w AF	w/o AF	w AF	w/o AF	w AF	w/o AF
2										
3										
4										
5										
…										
50										

9.1.3.5 Transferability of test results

The test results can replace full-scale wind turbine test of active filtering functionality.

9.1.4 Frequency depended Impedance measurement

9.1.4.1 Introduction

The wind turbine frequency-dependent equivalent impedance is crucial in harmonic propagation and small-signal stability studies. Small-signal wind turbine impedance is a part of the Thevenin or Norton model described in IEC 61400-21-3.

Therefore, impedance measurement tests are required for harmonic modelling as well as harmonic model validation for wind turbines and converters.

The aim of this chapter is to provide a general test methodology for the harmonic impedance measurement based on voltage or current perturbations in a test environment.

Note: Different methods, rather than the proposed test method in this chapter, might be used for the impedance measurement and harmonic model validation. However, the applied methods shall provide a procedure to verify the accuracy and reliability of the results.

9.1.4.2 Test setup & test conditions

The measurement shall at least be performed on a category 2b test bench as described in chapter 7.

The DUT shall include at least the components and control functions as defined in Annex B.2.

A test device with capability of small-signal current or voltage perturbation injections is required as illustrated in Figure 33 respectively. Accordingly, the perturbation test device can be a separate unit in series or parallel connection with the DUT. Each perturbation is a single-frequency component (single-tone) or a group of frequencies (multi-tone) with small amplitudes. The measurement equipment should have high resolution to measure the small-signal response of the DUT against perturbations.

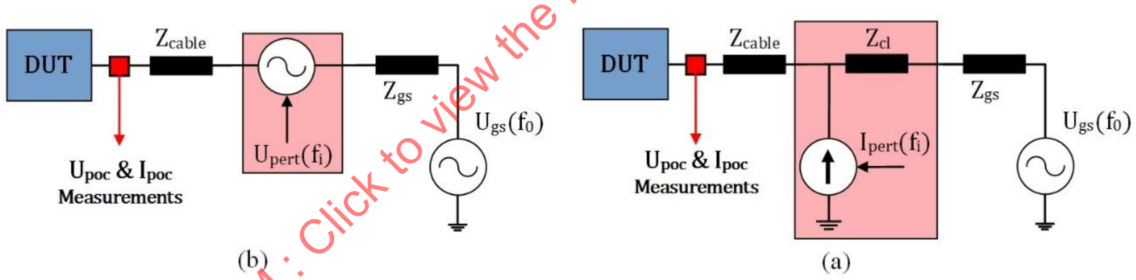


Figure 33 - Generic topology of (a) current and (b) voltage perturbation tests [1].

Alternative a grid emulator, as shown in Figure 34, for emulation of the AC grid ($U_{gs}(f_0)$) as well as the voltage perturbation ($U_{pert}(f_i)$) can be used.

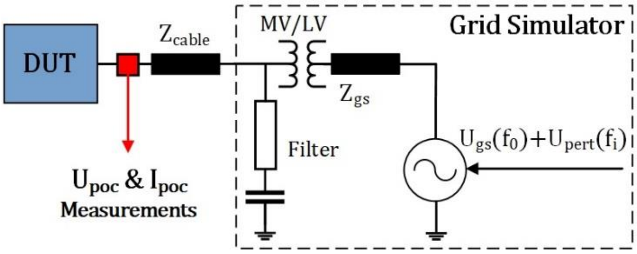


Figure 34 - Example of a grid emulator structure for voltage perturbation application [1].

Note: To minimize the coupling effects of the grid emulator on the test result, it is recommended to perform the test with an open-loop control for the perturbations, which means using set points for $U_{pert}(f_i)$ without control feed-backs. However, special considerations might be required for open-loop voltage injections. Thus, it is recommended to evaluate the test procedure in no-load condition first and then perform the tests with DUT. Depending on the output filter, transformer characteristics and switching frequency of the grid emulator, it is possible to perform voltage perturbation tests for an acceptable range of frequencies

9.1.4.3 Test & measurement procedure

The impedance measurement test methodology is given Figure 35.

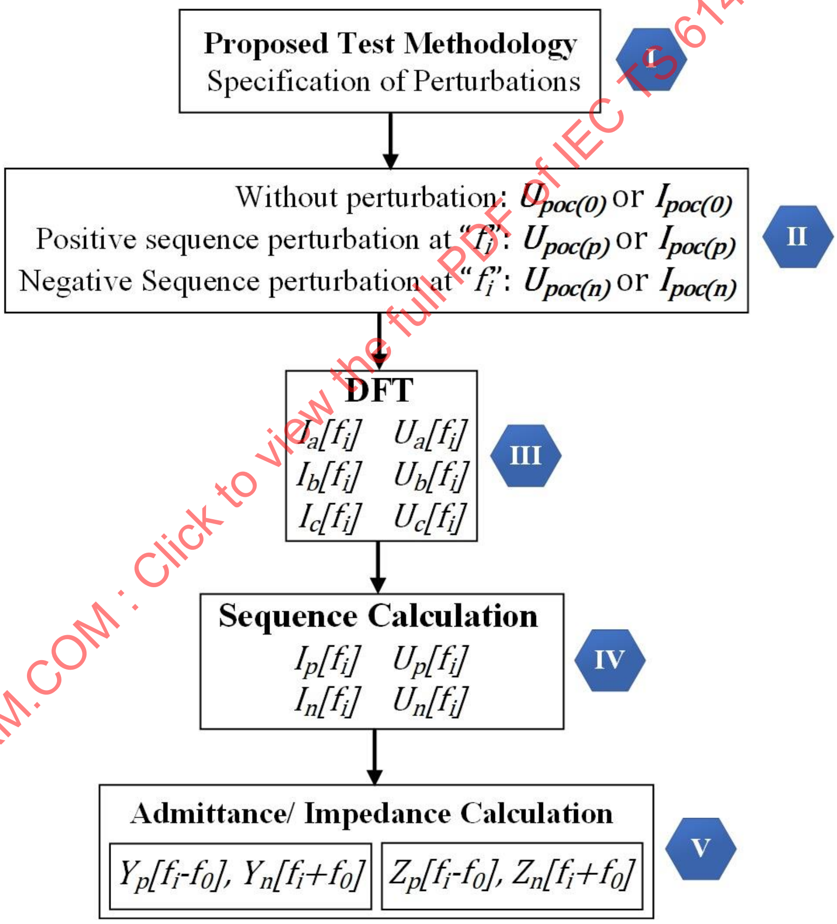


Figure 35 - Impedance measurement test methodology for wind turbines using perturbation tests

The methodology consists of five steps as follows:

I) Specification of Perturbations:

First, the specification of perturbations should be chosen based on the DUT characteristics and application of the test results. In Table 18, the test specification is categorized based on the voltage or current perturbation methods and frequency ranges. Accordingly, the maximum amplitude of the perturbations, frequency steps and power set-points should be specified for the test procedure as follows:

- Within the given range for voltage ($U_{poc}(f_i)$) or current ($I_{poc}(f_i)$) perturbation tests, smaller values can be chosen for testing of Type III WTs. In addition, higher values within the given range can be chosen for the grid emulators with lower short circuit ratio.
- The perturbation frequency shall start from the minimum frequency (f_{min}) and increase with the frequency steps (e.g., 9Hz, 9+2Hz,9+4Hz…). Lower frequency steps can be used for more precise impedance measurements locally near the potential resonance frequencies.
- It is recommended to choose the maximum frequency perturbation to less than cut-off frequency of the grid emulator's output filter ($f_{pmax} < f_{cut\text{-}off(gs)}$).
- To achieve an accurate impedance model, different power set-points shall be tested.
- The period of injections is preferably 3 seconds to achieve 1Hz or 0,5Hz resolutions in DFT calculations. It can be chosen up to 11 seconds to provide 0,1Hz resolution.

Table 18 - Specification of voltage or current perturbation tests

Frequency range	$f_{min} < f_p < f_0$	$f_0 < f_p < 2f_0$	$2f_0 \leq f_p$
Voltage perturbation ($U_{poc}(f_i)$)	0,4%-0,8% p.u.	1%-2% p.u.	1%-2% p.u.
Current perturbation ($I_{poc}(f_i)$)	4%-8% p.u.	2%-4% p.u.	1%-2% p.u.
Minimum frequency f_{min} (Hz)	9Hz	f_0+1 Hz	$2f_0$+1 Hz
Maximum frequency steps (Hz)	2Hz		
Power set-points (p.u.)	0,1; 0,5; 1,0		
Perturbation duration	3-11 seconds		

II) Positive and Negative Sequence Perturbations:

In order to measure a full response of the DUT against perturbations, it is required to perform tests for positive and negative sequence perturbations separately. The sequence-domain impedance is recommended since it can be used for power system stability studies easily.

In Figure 35, $U_{poc(p)}$ and $I_{poc(p)}$ are referring to three-phase positive sequence voltage or current perturbations for a range of frequencies. Similarly, $U_{poc(n)}$ and $I_{poc(n)}$ depict the negative sequence injections. The time-domain three-phase currents and voltages shall be measured for each perturbation.

III) Discrete-Fourier Transform (DFT):

The DFT of the three-phase measured data for each perturbation shall be calculated according to IEC 61400-21-1. To achieve 1Hz resolution in the harmonic spectrum, 1 second DFT window is recommended.

IV) Sequence calculations:

In this step, the positive and negative sequence voltage and currents shall be calculated for each perturbation frequency from the three-phase voltage and current harmonic spectrums. In this way, $U_{p(p)}[f]$, $U_{n(p)}[f]$, $I_{p(p)}[f]$, $I_{n(p)}[f]$ shall be derived from positive sequence perturbations and $U_{p(n)}[f]$, $U_{n(n)}[f]$, $I_{p(n)}[f]$, $I_{n(n)}[f]$ shall be calculated from negative sequence perturbation tests. The sequence-domain transformation of three-phase voltages can be calculated as follows:

$$\begin{bmatrix} U_p \\ U_n \\ U_0 \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & \alpha & \alpha^2 \\ 1 & \alpha^2 & \alpha \\ 1 & 1 & 1 \end{bmatrix} \begin{bmatrix} U_a \\ U_b \\ U_c \end{bmatrix}$$

Where $\alpha = 1\measuredangle 120^0$. Similar calculations can be performed for current components.

V) Admittance or Impedance Calculations:

According to the proposed methodology in Figure 35, the calculation of admittance or impedance matrices shall be based on the sequence-domain calculations of the three different measurement data sets:

(1) Normal operation without perturbation ($U_{p(0)}, U_{n(0)}, I_{p(0)}, I_{n(0)}$).

(2) Positive sequence perturbation test at f_i ($U_{p(p)}, U_{n(p)}, I_{p(p)}, I_{n(p)}$).

(3) Negative sequence perturbation test at f_i ($U_{p(n)}, U_{n(n)}, I_{p(n)}, I_{n(n)}$).

The admittance matrices shall be derived as follows:

$$Y_{pp}(f_i - f_0) = \frac{I_{p(p)} - I_{p(0)}}{U_{p(p)} - U_{p(0)}} = \frac{\Delta I_{p(p)}}{\Delta U_{p(p)}}$$

$$Y_{nn}(f_i + f_0) = \frac{I_{n(n)} - I_{n(0)}}{U_{n(n)} - U_{n(0)}} = \frac{\Delta I_{n(n)}}{\Delta U_{n(n)}}$$

Similarly, the impedance matrices shall be derived as follows:

$$Z_{pp}(f_i - f_0) = \frac{U_{p(p)} - U_{p(0)}}{I_{p(p)} - I_{p(0)}} = \frac{\Delta U_{p(p)}}{\Delta I_{p(p)}}$$

$$Z_{nn}(f_i + f_0) = \frac{U_{n(n)} - U_{n(0)}}{I_{n(n)} - I_{n(0)}} = \frac{\Delta U_{n(n)}}{\Delta I_{n(n)}}$$

Note: Using the positive sequence perturbation data at frequency of "f_i", the positive sequence admittance/impedance can be calculated at "f_i-f_0" ($Y_{pp}(f_i - f_0), Z_{pp}(f_i - f_0)$). While, using negative sequence perturbation test data at "f_i", the calculated negative sequence admittance/impedance shall be for "f_i+f_0" ($Y_{nn}(f_i + f_0), Z_{nn}(f_i + f_0)$). Further investigations on the test results are out of the scope of this chapter and can be found in [1].

Note: For higher frequencies ($f_p > f_{cut\text{-}off}$), the perturbation tests are optional and the admittance/impedance can be calculated by performing the test procedure (Fig.4) on simulation models.

Note: In the case of model validation applications, the extracted model from the test methodology shall be compared with the model given by the DUT owner. Multi-tone perturbation tests can be used for model validation application as well. Note that the model validation procedure is out of the scope of this chapter.

9.1.4.4 Measurement data assessment

The accuracy of measured data depends on the measurement equipment resolution and potential environment noise level. Since the tests shall be done in the small-signal range, high precision measurement equipment is required. Class I measurement instruments are recommended for current and voltage measurements according to IEC 61000-4-7. The measurement instruments with higher precision can be used optional for a better accuracy.

1) Effects of Test Procedure:

The results of the test and measurement data depends on the perturbation method, frequency couplings and potential undesired distortions. Therefore, three evaluation criteria are suggested as follows:

a) Total Harmonic Distortion (THD) of Voltage and Amplitude of the Intended Perturbation: If a perturbation contains undesired harmonic components in a considerable level, the result of tests would have frequency couplings with the undesired harmonic components and would lead to wrong data and calculations. Therefore, amplitude of the injection and the THD of the voltage excluding the intended perturbation could be considered as trust criteria for the measurement data.

b) Vicinity Harmonic Components: In addition to THD, the undesired harmonic components in the vicinity of the intended perturbation can affect the trustworthy of the test results. The main couplings can be observed for “$2f_0 \pm f_i$“ and “$f_i \pm f_0$“ frequencies. Therefore, the injections should not contain considerable undesired harmonic components in the vicinity of the intended perturbation frequency, especially in the range of absolute values of $|f_i \pm 2f_0|$. However, in the case of high frequency ranges, inevitable switching harmonics would be observed, but it should be proven that such harmonics are not results of the perturbation tests.

c) Differential Phase Angle: A stable phase angle between harmonic components of voltage and current over the injection period can be another trust criterion which confirms steady-state and stable condition of the converter response against the injection. This factor can be evaluated by time-domain illustrations or a probability factor over the injection period.

9.1.4.5 Documentation

The applied perturbation method and settings as well as the results of these test must be documented in the test reports, including:

- Description of the test setup / Real time simulator setup
- Measurement setup according to chosen test procedure
- Documentation of the control mode / operational mode of the DUT.
- Table of the calculated frequency dependent positive and negative sequence (Thevenin or Norton) Impedance for each power level as stated Table 18, in the validated frequency range as shown in e.g. Table 19

Table 19 - Example of representation of the harmonic impedance

Harmonic / order	Frequency	Harmonic impedance – positive sequence		Harmonics impedance – negative sequence	
[n]	Hz	Resistance, R [Ω]	Reactance, X [Ω]	Resistance, R [Ω]	Reactance, X [Ω]
2	100				
3	150				
4	200				

5	250				
…	…				

Note: The equivalent harmonic impendence representation of the DUT is a small-signal representation and therefore sensible to the applied control mode/ operational mode of the DUT .

A report template is given in Annex A.

9.1.4.6 Transferability of test results

The test results can replace full-scale wind turbine measurements.

9.2 Steady state operation

9.2.1 Voltage capability

The aim of this test is to validate the capability of the DUT to operate within a defined voltage range.

9.2.1.1 Description

In this test, the voltage range capability of the DUT under steady state conditions shall be validated, against the capability chart given from the manufacturer.

9.2.1.2 Test setup & test conditions

The measurement shall at least be performed on a category 2b test bench as described in chapter 7.

The test bench grid system shall be able to vary and provide a stable voltage supply in the range of min +/- 2 % of the desired voltage capability of the DUT.

The grid system shall be able to adjust the voltage operating points with a maximum error of 1 % of Un.

The DUT shall include at least the components and control functions as defined in Annex B.2.

Components not affected by voltage variations can be excluded from the test.

9.2.1.3 Test & measurement procedure

The test shall be carried out with the following start conditions:

- The DUT shall be operated at nominal voltage and nominal power as declared by the manufacturer.
- The DUT shall operate at the nominal power factor for the operating point as stated by the manufacturer.

At least 2 tests shall be conducted, one at each voltage capability limit.

The voltage at the terminals of the DUT shall be changed according to the following sequence:

- The voltage shall be reduced to the minimum voltage and maintained for a minimum of 10 min or the defined minimum capability time of the DUT.
- The voltage shall be increased to its nominal value and maintained for a minimum of 10 min;
- The voltage shall be increased to its maximum limit and maintained for a minimum of 10 min time or the defined maximum capability time of the DUT;
- The voltage shall be decreased to the nominal value.

The voltage shall be maintained stable during the entire test and the voltage variations during the test shall not exceed 1 % of Un.

During the test the positive sequence voltage and active and reactive power shall be measured at the terminals of the DUT with an average time of 0,2 s

Note: Additional test of specific voltage levels, can be performed with the same procedure.

9.2.1.4 Documentation

The following parameters shall be documented in tables and graphs as shown in for example Annex A:

- DUT documentation of the voltage capability range including their nominal voltage and limits
- Positive sequence voltage measured at the DUT terminals with and average time of 0,2 s
- Measured active and reactive power with and average time of 0,2 s

9.2.1.5 Transferability of test results

The test results are supplementary to the wind turbine measurements and the test results can replace full-scale wind turbine measurement.

9.2.2 Frequency capability

The aim of this test is to validate the capability of the DUT to operate within a defined frequency range.

9.2.2.1 Description

In this test, the frequency range capability under steady state conditions shall be validated, against the frequency range capabilities given from the manufacturer.

9.2.2.2 Test setup & test conditions

The measurement shall at least be performed on a category 2b test bench as described in chapter 7.

The test bench grid emulator shall be able to vary and provide a stable frequency and voltage supply in the range of min +/- 0,5 Hz of the desired frequency capability of the DUT.

The DUT shall include at least the components and control functions as defined in Annex B.2.

Components not affected by frequency variations can be excluded from the test.

9.2.2.3 Test & measurement procedure

For the determination of the frequency capability the following procedure shall be applied:

The test shall be carried out with the following start conditions:

- The DUT shall be operated at nominal frequency, nominal voltage and nominal power as declared by the manufacturer.
- The DUT shall operate at the nominal power factor for the operating point as stated by the manufacturer.

At least 2 test shall be conducted one at each frequency capability limit / frequency level (e.g. 47 and 52 Hz)

The frequency at the terminals of the DUT shall be slowly changed according to the following sequence:

- The frequency shall be reduced to the minimum frequency level and maintained for a minimum of 10 min or the defined min capability time of the DUT.
- The frequency shall be increased to its nominal value and maintained for a minimum of 10 min;
- The frequency shall be increased to its maximum limit and maintained for a minimum of 10 min time or the defined minimum capability time of the DUT.
- The frequency shall be decreased to the voltage nominal value.

The frequency shall be maintained stable during the entire test and the frequency variations during the test shall not exceed 0,1 Hz.

During the test the frequency, positive sequence voltage, active and reactive power shall be measured at the terminals of the DUT with an average time of 0,2 s.

Note: Additional test of specific frequency levels, can be performed with the same procedure.

9.2.2.4 Documentation

The following parameters shall be documented in tables and graphs as shown in Annex A:

- DUT documentation of the frequency capability range including their nominal frequency and limits
- Frequency at the DUT terminals measured with an average time of 0,2 s
- Positive sequence voltage measured at the DUT terminals with and average time of 0,2 s
- Measured active and reactive power with and average time of 0,2 s

9.2.2.5 Transferability of test results

The test results are supplementary to the wind turbine measurements and the test results can replace full-scale wind turbine measurement.

9.2.3 Current Unbalance Factor in an unbalanced system

9.2.3.1 Description

The aim of the measurement is to determine the current unbalance factor of the PGU when the voltage unbalance induced by the grid emulator is set to a specific value (e.g. 2%±0,5 %).

9.2.3.2 Test setup & test conditions

The measurement shall at least be performed on a category 2b test bench as described in chapter 7.

The DUT shall include at least the components and control functions as defined in Annex B.2.

For the generation of a voltage unbalance system the following possibilities are proposed:

a) Use of Grid Emulator with a voltage unbalance, see Figure 31 in chapter 9.1.1.2

b) Use a constant voltage and impedance Grid Emulator and add the voltage unbalance by a shunt load, ohmic or inductive see Figure 32 in chapter 9.1.1.2.

The grid emulator or the shunt load shall at least be able to set the voltage unbalance factor to at least 2% with an accuracy of ± 0,5%.

9.2.3.3 Test & measurement procedure

The current unbalance factor of the DUT is determined, while the DUT is operating in an unbalanced system.

- The test shall be done in steady states at 10, 20, 30, … 100% P_n.
- The positive sequence reactive power shall be set to zero.
- The drivetrain shall be in a steady state for minimum 1 minute in each step.
- 3-phase voltage and currents shall be recorded, and 1-minute averages of voltage and current unbalances shall be calculated in each step.

The positive sequence voltage U1 and current I1 as well as the negative sequence voltage U2 and current I2 shall be calculated according to IEC 61400-21-1.

9.2.3.4 Documentation

The measured 1-minute values of the current unbalance and the active power positive sequence system component are represented as an IUF-P diagram. The measurement results shall be presented in a table as mean values of each power bin, as defined, for example, in Table 20. The maximum current unbalance factor as a 1-minute value shall be explicitly given.

Table 20 - Current unbalance factor in an unbalanced system

P [p.u.]	Q [p.u.]	U1 [p.u.]	U2 [p.u.]	UUF	I1 [p.u.]	I2 [p.u.]	IUF
~0,1	~0,0			2% ± 0,5%			
~0,2	~0,0			2% ± 0,5%			
~0,3	~0,0			2% ± 0,5%			
~0,4	~0,0			2% ± 0,5%			
~0,5	~0,0			2% ± 0,5%			
~0,6	~0,0			2% ± 0,5%			
~0,7	~0,0			2% ± 0,5%			
~0,8	~0,0			2% ± 0,5%			
~0,9	~0,0			2% ± 0,5%			
~1.0	~0,0						

9.2.3.5 Transferability of test results

The test results are supplementary to the wind turbine measurements and the test results can replace full-scale wind turbine measurement as supplement the results from chapter 8.2.5.

9.3 Control performance

9.3.1 Grid Impedance variations

9.3.1.1 Description

The aim of the measurement is to determine the stability of the DUT controller due to impedance variations in the grid.

9.3.1.2 Test setup & test conditions

The measurement shall at least be performed on a category 1b test bench as described in chapter 7.

The grid emulator shall be able to, variate the grid impedance / reduce the short circuit ratio (SCR) and weaken the grid strength down to a predefined level e.g. to 1 with respect to the S_n of the DUT.

Alternative the impedance variation can be performed with physical impedances.

The DUT shall include at least the components and control functions as defined in Annex B.2.

9.3.1.3 Test & measurement procedure

The test shall be carried out at minimum at two different test levels, with the following start conditions:

Test condition 1 (100 % of P_n):

- The DUT shall be operated at nominal voltage and nominal power as declared by the manufacturer.
- The DUT shall operate at the nominal power factor for the operating point as stated by the manufacturer.

Test condition 2 (50 % of P_n):

- The DUT shall be operated at nominal voltage and 50 % of P_n nominal power as declared by the manufacturer.
- The DUT shall operate at the power factor for the operating point as stated by the manufacturer.

During the test the impedance shall be varied in the following way, for both test conditions stated above:

- The impedance of the grid is increased step-wise from a starting impedance Z_1 (SCR around 10) to a maximum impedance Z_n (e.g. SCR = 1). The impedance steps shall be chosen to cover equally the SCR range with the respective X/R ratio.
- The time duration for the steps should be chosen long enough to ensure that the system has been stabilized.

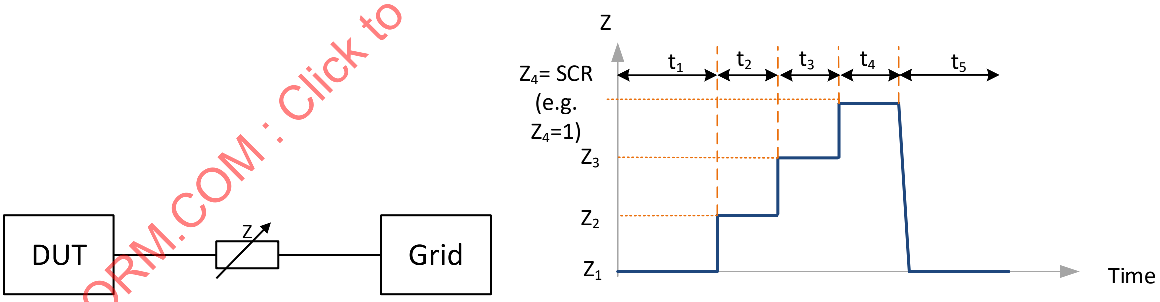


Figure 36 - Impedance variation – example of steady state procedure & stepwise impedance increase

The grid impedance variations as shown above can performed with a grid emulator or physical impedances.

The impedance / SCR setting shall be maintained stable during the entire test and the variations during the test shall not exceed 1 % of the defined impedance.

During the test the positive sequence voltage and active and reactive power shall be measured at the terminals of the DUT with an average time of 0,2 s, with a sample rate of 20 kHz.

9.3.1.4 Documentation

The following parameters shall be documented in tables and graphs as shown in for example Annex A:

- Impedance steps and values as complex value
- Positive sequence voltage measured at the DUT terminals with and average time of 0,2 s
- Measured positive and negative sequence current with and average time of 0,2 s
- Measured active and reactive power with and average time of 0,2 s

9.3.1.5 Transferability of test results

The test results are supplementary to the wind turbine measurements and the test results can replace full-scale wind turbine measurements.

9.3.2 Island operation

9.3.2.1 Introduction

The aim of the test is to validate the DUT behaviour under Island operation, where the DUT is disconnected from the main power supply. The described test procedure defines the procedure for testing the stand-alone islanding operation and describes not the island detection or re-synchronization.

9.3.2.2 Test setup & test conditions

The measurement shall at least be performed on a category 1b test bench as described in chapter 7.

The test can be performed with passive tuned RLC loads or with a grid emulator, which is capable to emulate a fixed RLC load. Figure 37 shows the setup with a variable RLC-load.

The DUT shall include at least the components and control functions as defined in Annex B.2.

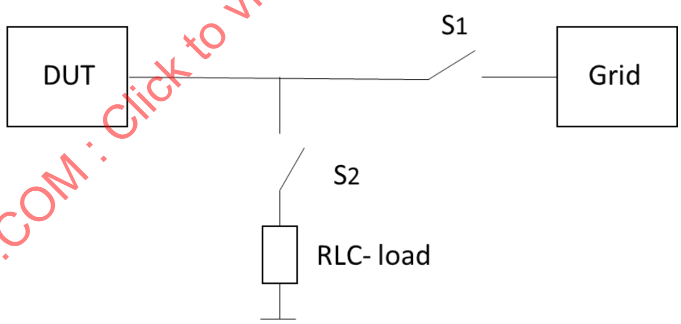


Figure 37 - Single line diagram of RLC load connected with DUT

9.3.2.3 Test & measurement procedure

The test shall be carried out with the following start conditions:

- The DUT shall be operated at nominal frequency, nominal voltage and an active power setting according to the defined test level.
- The DUT shall operate at the nominal power factor for the operating point as stated by the manufacturer.

It is recommended to do the test at minimum three power levels for P_n >= 20%, > 50 % and > 80% of the nominal power of the DUT.

The following test sequence shall be applied for the defined test levels:

1. Stable operation of the DUT at the defined output power
2. Tuning of RLC loads / to be equal to the power production
3. Opening of the grid circuit breaker / switch grid emulator operation to a fixed RLC- load operation
4. DUT operation in islanding mode
5. After the system has been stabilized the DUT shall be disconnected.

9.3.2.4 Documentation

The following information shall be given for the test:

- Description of the test setup / Real time simulator setup
- Description of the impedance of the transformer and the passive components of the DUT
- Impedance or emulated RLC load and power production of the DUT

The following parameters shall be documented in tables and graphs as shown in for example Annex A

- Measured frequency at the DUT
- Measured positive and negative sequence voltage measured at the DUT
- Measured positive and negative sequence current
- Measured active and reactive power form the DUT

All variables shall be measured from 1 se before the Island operation until 5 s after the system has been stabilized.

9.3.2.5 Transferability of test results

The test results are supplementary to the wind turbine measurements and the test results can replace full-scale wind turbine measurement.

9.4 Dynamic performance

9.4.1 RoCoF – real df/dt – capability

9.4.1.1 Description

The DUT behavior during grid events that cause a fast change of frequency in a short time frame shall be tested.

The aim of these tests is to prove the DUT's capability to operate through fast changes of frequency (RoCoF).

9.4.1.2 Test setup & test conditions

The measurement shall at least be performed on a category 1b test bench as described in chapter 7.

The grid emulator must be able to control the frequency of the emulated grid with required dynamics, typically 1 Hz/s to 6 Hz/s.

The DUT shall include at least the components and control functions as defined in Annex B.2.

9.4.1.3 Test & measurement procedure

The test sequence consists of a rapid change of the frequency typically in a range of 1 Hz/s to 6 Hz/s starting from the nominal frequency.

The test shall be carried out, by increasing or decreasing the grid frequency by the specified constant rate of change of frequency (df/dt) from rated frequency. The test has to be occurred so that the DUT does not trip, with increasing the test slope (df/dt) condition in 1,0 Hz/s steps, as e.g. defined in IEC 61400-21-1: 2019, up to the RoCof capability defined by the manufacture.

9.4.1.4 Documentation

The applied settings as well as the results of these test must be listed in the test reports, a report template is given in Annex A.

- Reference value of the protection level and release time
- Description of control settings / operational mode

Time-series of:

- Measured positive sequence active power output at the grid connection point
- Measured frequency or the frequency reference value f_{sim}, measured as 0,1 s average value at the grid connection point.

Measurements include data 5 s prior and 5 s after to the start of the RoCoF (df/dt) event.

9.4.1.5 Transferability of test results

The test results are supplementary to the wind turbine measurements and the test results can replace full-scale wind turbine measurement.

9.4.2 Phase jump

9.4.2.1 Description

Phase jump is used for Verification of the insensibility on automatic reconnections in case of phase discordance. The DUT behaviour during grid events that cause a fast change of the voltage vector surge in a short time frame shall be tested.

The aim of these tests is to prove the correct operation of the DUT without tipping during operation.

9.4.2.2 Test setup & test conditions

The measurement shall at least be performed on a category 1b test bench as described in chapter 7.

The DUT shall include at least the components and control functions as defined in Annex B.2.

9.4.2.3 Test & measurement procedure

The test can be performed with either:

a) A grid emulator connected to the DUT

b) Or the DUT connected to the public grid

9.4.2.3.1 Test with a grid emulator (option a)

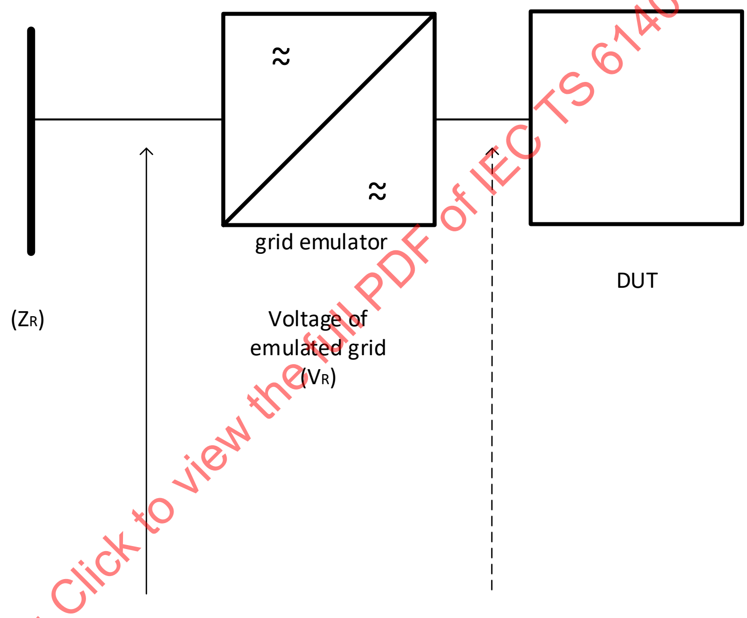


Figure 38 - Example of a test setup with the grid emulator.

With reference to the diagram shown in Figure 38 - use of emulated grid:

- The grid emulator must be capable of producing a voltage phase jump on the output terminals of the converter of 90° and 180°, respectively.
- Generator operating at power level compatible with the characteristics of the test circuit and with a unitary power factor.
- V_R: voltage of emulated grid;

The DUT must be brought into operation at nominal power. The DUT shall operate under the conditions set for at least 5 minutes.

At the end of the stabilization period, 2 tests must be conducted in sequence, inducing a transient which produces suddenly a phase angle displacement on the V_R simulated grid voltage of the grid emulator about 180° in a time range ≤ 10ms and 90° in a time range ≤ 5ms.

9.4.2.3.2 Test on real grid (option b)

Test on distribution grid through coupling transformer:

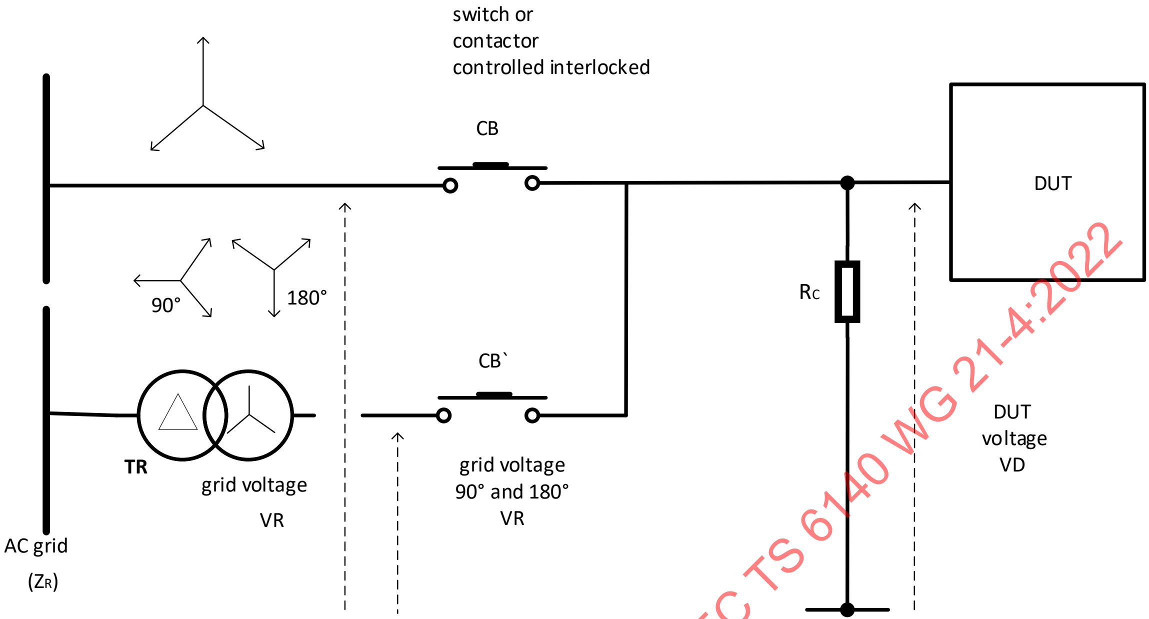


Figure 39 - Circuit for the verification of the immunity on automatic reconnection in case of phase discordance through coupling transformer.

With reference to the diagram shown in Figure 39 use of a coupling transformer:

- TR: transformer with open columns, to be configured YYn or DYn depending on the test to be performed.
- DUT operating at a level of power compatible with the characteristics of the test circuit and with unitary power factor.
- Rc: resistive load ballast weight with power equal to the nominal power of the DUT.
- V_R: voltage of the distribution grid.
- V_R': voltage phase shifted relative to the distribution grid of 90° and 180° depending on the test to be performed.
- V_D: voltage applied to the DUT.

The DUT must be set into operation at the nominal power. The DUT shall operate under the conditions set for at least 5 minutes

Check that, for at least 1 minute, the current through the CB switch is below 2% of the nominal current. The value measured must be included in the test report.

Open the CB contactor and close the CB' contactor, in a coordinated and instantaneous manner (less than the difference on the opening and closing times). The ballast resistance damps the electrical transients on the output of the DUT and prevents a possible disconnection from the grid.

The disconnection of the DUT or the protections tripping can only occur downstream of the complete closing of the CB' contactor.

Two (2) tests must be conducted, with phase angle shift at closing of 180° and 90° respectively. For this purpose, the vector group of the TR transformed must be reconfigured appropriately.

9.4.2.4 Documentation

The following information shall be given and stated as part of the test report,

- Description of the test setup / Real time simulator setup
- The angle between the voltage before and after the phase jump, with a measurement error of max 1°.
- Measured positive and negative sequence voltage measured at the DUT
- Measured positive and negative sequence current
- Measured active and reactive power from the DUT
- Instantaneous voltage and current measurements from 20 ms before the phase jump event until min 200 ms after the event.

The measurements results shall be in graphs and tables as e.g. defined in Annex A.

9.4.2.5 Transferability of test results

The test results are supplementary to the wind turbine measurements and the test results can replace full-scale wind turbine measurement.

9.5 Grid forming operation (Optional)

9.5.1 Description

Grid forming operation is a converter capability aiming to control voltage amplitude and frequency – both in island mode or when connected to a grid with additional power sources. Grid forming control of converter is usually intended to provide – besides active and reactive power – a contribution to the services (e.g. providing inertia and short circuit power) needed to run a grid equipped with loads or grid following converter systems.

Grid forming control

- of converters (in power plants, HVDC substations or STATCOMs) is needed if 100% converter based power generation without synchronous generators or synchronous condensers is intended.
- with inertia and short circuit power provision is needed to provide black start capability to re-energize large grids. For black start capability, additional energy sources are needed to start up a wind turbine.
- can be tested both at turbine or component level (or a possible combination of both).
- typically responds to voltage amplitude or frequency (voltage angle) changes within less than ¼ line period. Therefore, some extensions of test setups described before are necessary to evaluate grid forming capabilities of converters.

Specific requirements for grid control may depend on the grid operator. FNN [15] proposes the following tests:

1. Phase jump
2. Phase jump followed by a linear frequency change in the main voltage
3. Voltage jump (UVRT and OVRT)
4. Occurrence of a negative system
5. Occurrence of harmonics
6. Occurrence of subharmonics
7. Change in grid impedance

resulting in additional evaluations of the results of tests methods described in the chapter of this TS. In these cases, it is assumed, that the grid is voltage controlled and strong.

In addition, the following test is required:

8. Island network formation with current applying regulated voltage source

In this case, it is assumed, that the grid is current controlled and weak.

Figure 40 describes the test setup including necessary extension for testing grid forming converter control capabilities. The test setup in described in a way that allows different forms of validation (Controller software only, controller in a HiL environment, hardware test) can use the same topology.

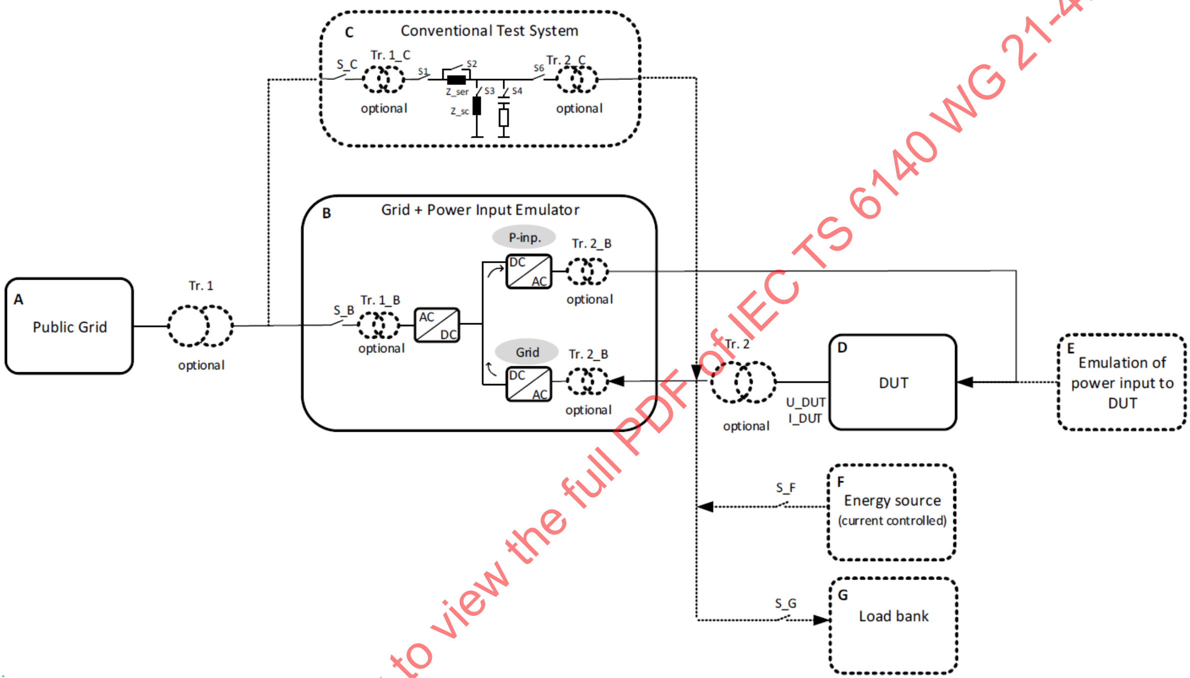


Figure 40 - Test setup extension for testing grid forming converter control capabilities

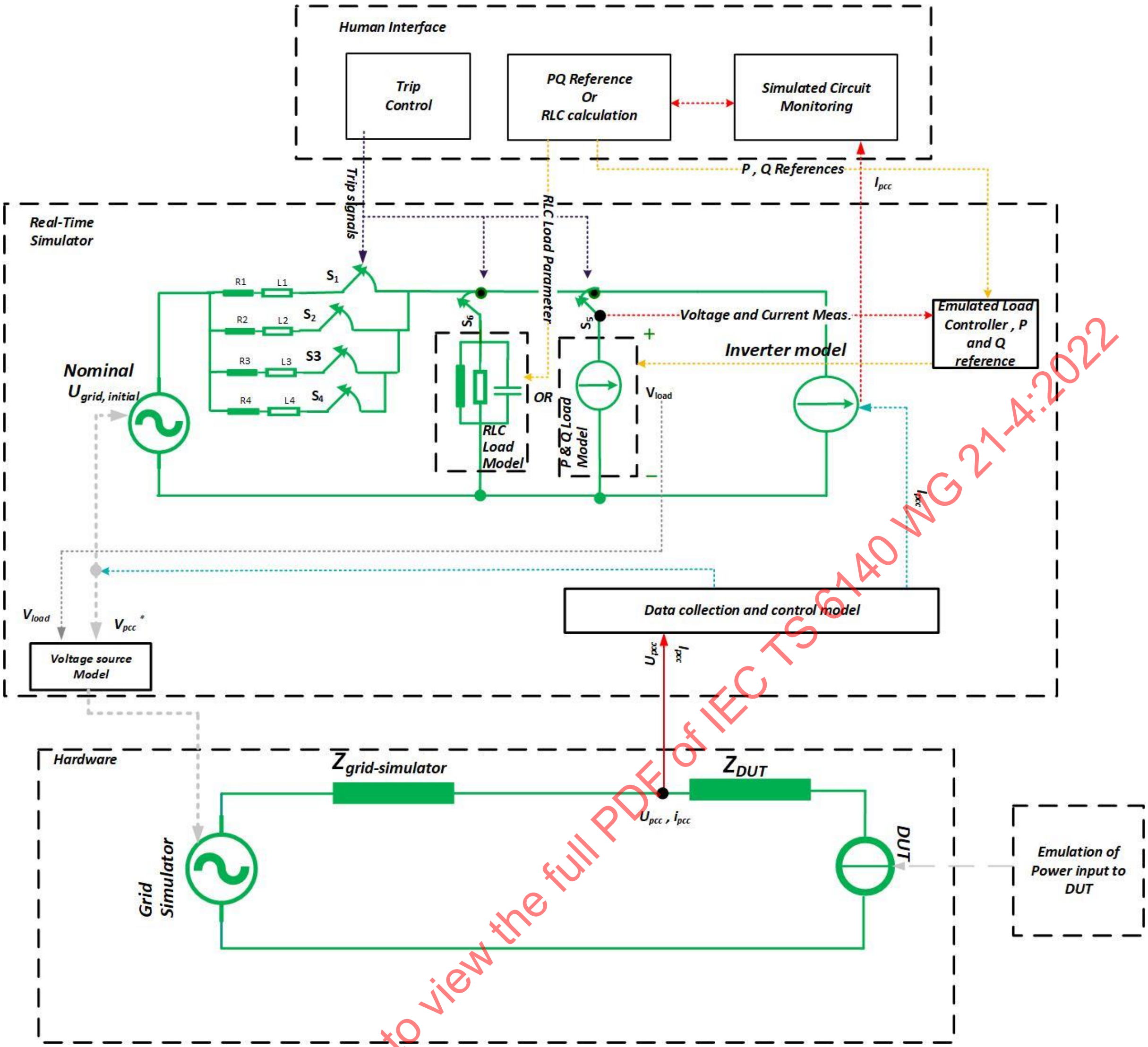
Table 21 - Description of components shown in Figure 40

Item	Designation	Description
A	Public grid	Generators, transformers, lines and loads operating at different voltage levels and connected in one network. NOTE: Tr. 1 can be applied to step up or step down the voltage as appropriate.
B	Grid + power input emulator	Grid emulator: Device used for emulating steady state values or dynamic changes of voltage, frequency or impedance. Power input emulator: Device for emulating the power input of the DUT. Depending on the component level, it replaces e.g. the aerodynamics (rotor

		and pitch system) and the generator for testing grid forming on a converter system. NOTE: May or may not include step-up or step-down transformers Tr. 1_B and Tr. 2_B
C	Conventional test system	FRT equipment made up of voltage divider suitable for both UVRT and OVRT testing. NOTE: May or may not include step-up or step-down transformers Tr. 1_C and Tr. 2_C
D	DUT	Device under test (turbine or component level). NOTE: Tr. 2 would be the step-up transformer normally applied for the DUT, if applicable.
E	Emulation of power input to the DUT	Replaces the rotating prime mover which, in the case of a wind turbine, would be the shaft driven by the rotor blades.
F	Energy source	Used for islanding tests, where voltage and frequency are set to deviate from nominal values. NOTE: This might be needed, when the grid + power input emulator is not able to operate as current controlled load.
G	Load bank	Used for islanding tests, where voltage and frequency are set to deviate from nominal values. NOTE: This might be needed, when the grid + power input emulator is not able to operate as current controlled load.

9.5.2 Power Hardware in the loop (PHiL) implementation

A possible power HiL (PHiL) implementation of the hardware setup is shown in Figure 41. Table 21 describes hardware, real-time-simulator and human machine interface of the test setup.



2772

2773 **Figure 41 – Power Hardware in the loop (PHiL) implementation**

2774

Annex A(informative)

Report template

A.1 The final detailed report template will be provided together with the CDV

Information from the project leader to the Annex A: The Annex A is a summary of the defined documentation requirements from chapter 7, 8 and 9. The WG21 wants in this CD to have feedback on the suggested required documentation parts in the main document and will afterwards finalize the informative Annex A, with the same structure as defined in the IEC 61400-21-1.

The Annex A will include suggestions for the reporting of the measurement results. The formatting of the tables and the graphs is exemplary.

The Annex A of this standard will be structured in the same format as the IEC 614000-21-1 and the IEC 61400-27-2, including report templates, tables and time series, of the requested parameters, values, etc. as defined in the documentation subchapters of this standard.

In addition to the suggested test report format, the measured values should be provided in a standardized electronic format, as requested e.g. for the simulation model validation in 61400-27-2.

2792

Annex B
(informative)

Subsystems

B.1 Guideline test flow - functional, capability and performance test

This TS provides the measurement and test procedures test which can be used to replace site specific tests as defined in IEC 61400-21-1.

This technical specification is a supplement to the 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 procedures provide the basis for detailed simulation model validations and detailed validation of the electrical characteristics of components and subsystem.

The defined test and measurement procedures can be performed as a combination of functional-, capability-, and performance tests.

The combination of the different tests on subsystem and component level can afterwards, be used to verify the overall performance of the Wind turbine, as shown in Figure 2 and Figure 42

A detailed test overview and overview of the minimum subsystems, necessary for the verification and assessment of the electrical characteristics are shown in Table 22 and Table 23.

If it can be reasoned that the changes that have been implemented pose no significant risk of changing the electrical performance of the unit, then there is no need to perform new tests and measurements on the wind turbine with the changes or DUT. In these cases, the measurement and test results can be adapted to the other wind turbines within the product platform. A detailed guideline can be found in IEC61400-21-1 Annex F. In the cases of minor changes e.g. on the control function, the validation of the performance can be performed as a functional test, including the WT controller and a HiL setup with the necessary control interfaces.

In cases where minor changes in the subsystems requesting a refresh of partial 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.

Table 22 and Table 23, provides as well the overview of the necessary subsystems and components which are necessary for the functional (F), capability (C) and performance test (P).

The validation can be performed as a combination of functionality test, capability test and performance test. Where the final validation will be a combination of the different test categories.

The measurement results are finally used to validate theoretical analysis and numerical simulations models as well as electrical performance of the Wind Turbine, subsystems and components.

Figure 42 – gives an overview of the different test categories and strategies.

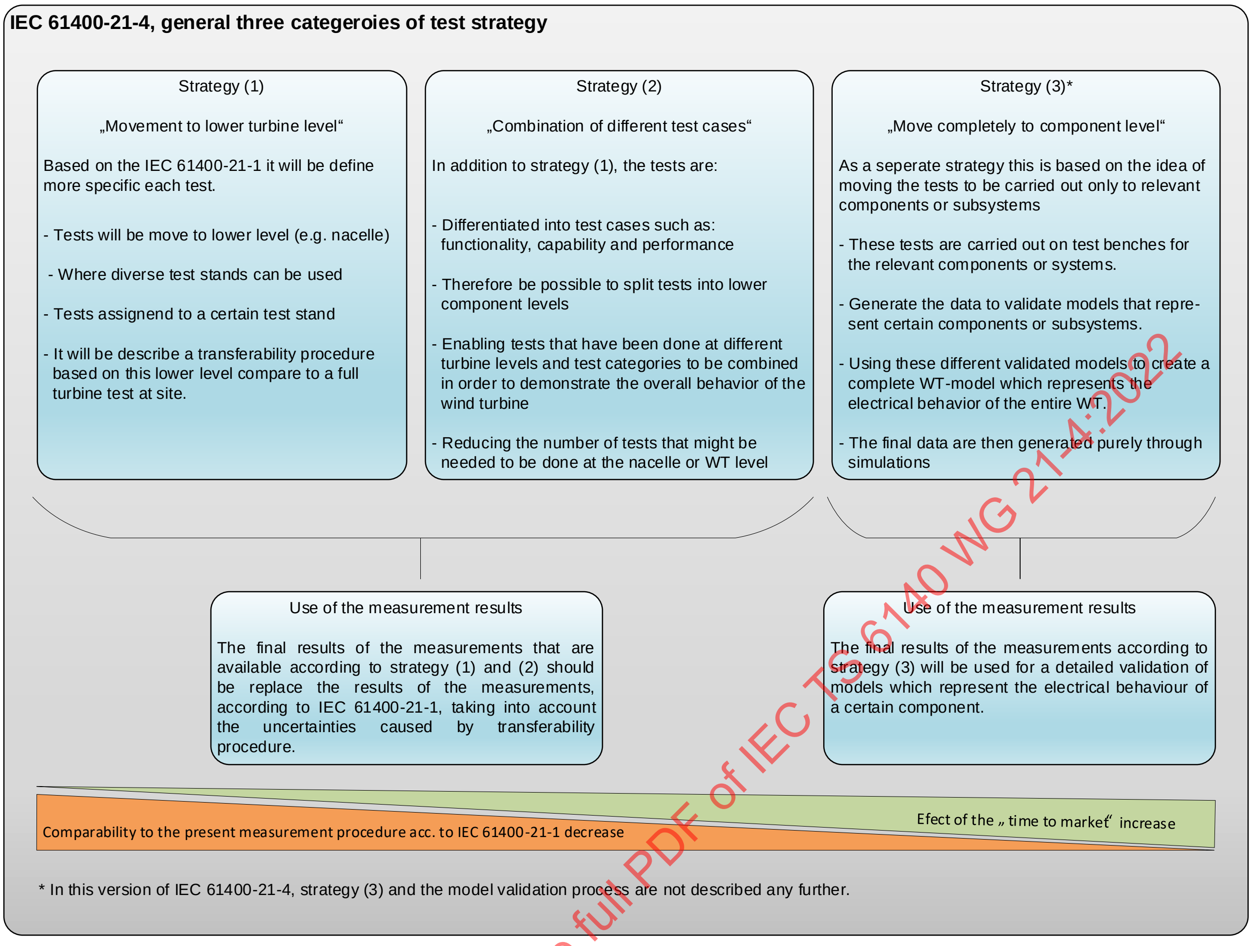


Figure 42 – Overview of test strategies

B.2 Overview of components, subsystems and control functions

Table 22 and Table 23 gives an overview of the major components subsystems and control functions, against the different measurements and test procedures as defined in this TS. The different columns defines therefore the minimum requirements for the DUT.

Each column defines therefore as a guidance the necessary parts and subsystems, which should be as minimum, included in the test system as DUT, to be able validate and perform the required measurements and tests.

The control functions are listed as functionality, instead of the physical HW (Turbine controller etc.), as the physical HW implementation of these controller functions can variate from WT type and manufacture.

Table 22 – Overview of components, subsystems and control functions according to chapter 8

Test	Chapter Nr.	test bench system	Functionality test	Capability test	Performance test	Converter System	Generator	Additional Cap- banks	Filter	Grid Power Control (active Power)	Grid Power Control (reactive Power)	Generator Power Control (or speed control)	Switch Gear (Circuit breaker / Contactor)	Transformer	Aux- equip.	Grid (FRT) Current Control	Grid Voltage Control	Grid Frequency control	Grid protection funtions	Hub	Blades (always emulated)	Pitch system	Pitch controller	Drive train (incl. Gearbox)
Flicker		Field test *			X																			
Switching operations		Field test *			X																			
Reconnection time		Field test *			X																			
Harmonics, Interharmonics - Higher frequencies		2b			X	P	P	P	P	P	P	P		P										P
Maximum Power		1a			X	P	P	P	P	P	P	P		P	P				P	P	P	P	P	P
Reactive power characteristic (Q=0)		2a			X	P	P(1,2,3)	P	P	P	P	P			P									
Reactive power capability		2b		X		C	C (1,2,3)	C	C	C	C	C		C										
Voltage dependency of PQ diagram		2b		X		C	C (1,2,3)	C	C	C	C	C		C			C							
Unbalance factor		2b			X	P	P	P	P			P		P		P								P
Active power control		2a	X		X	P	P			F,P		F,P								P	P	(P)	F,P	
Active power ramp rate limitation		1a or 2a	X		X	P	P			F,P		F,P								P	(P)	(P)	F,P	
Frequency control		2a	X		X	P	P			F, P		F, P	P					F,P	F,P					
Synthetic inertia		1a		X	X	P,C	P,C			P,C		P,C								P,C	P,C	P,C	P,C	P,C
Reactive power control		2b	X		X	P	P (1,2,3)	P			F,P													
UVRT		From 3a- 1 a	X	X	X	P,C	P,C	P	P,C	P,C,F	P,C,F	P,C,F	(P)	P,C	P	P,C,F	P,C,F	P,C,F	(P)	P*,C*	P*,C*	P*,C*	P*,C*	(P*),C*
OVRT		From 3a- 1 a	X	X	X	P,C	P,C	P	P,C	P,C,F	P,C,F	P,C,F	(P)	P,C	P	P,C,F	P,C,F	P,C,F	(P)	P*,C*	P*,C*	P*,C*	P*,C*	(P*),C*
Grid protection		3c	X										F						F					
Rate of change of frequency RoCoF (df/dt)		3c	X										F						F					

P: Perfomance test C: capability test F: Functional test

(1,2,3,4): refers to turbine type I, II, III and IV * Can be emulated

Table 23 - Overview of components, subsystems and control functions according to chapter 9

Test	Chapter Nr.	Test bench system	Functionality test	Capability test	Performance test	Converter System	Generator	Additional Cap- banks	Filter	Grid Power Control (active Power)	Grid Power Control (reactive Power)	Generator Power Control (or speed control)	Switch Gear (Circuit breaker / Contactor)	Transformer	Aux- equip.	Grid (FRT) Current Control	Grid Voltage Control	Grid Frequency control	Grid protection funtions	Hub	Blades (always emulated)	Pitch system	Pitch controller	Drive train (incl. Gearbox)
Flicker control		1b	X		X	P	P	P	P	F,P	F,P			P			F,P							P,C
Flicker and voltage change during switching operations		2b	X		X	P	P	P	P	F,P	F,P			P			F,P							
Active filter / Sink for harmonics		2b	X		X	P	P (1,2,3)	P	P	F,P	F,P			P			F,P							P(1,2,3)
Impedance measurements		2b			X	X	1,2,3	X	X	X	X			X		X	X							1, 2, 3
Voltage capablity		2b		X		C	C	C	C		C			C	C		C		C					
Frequency capability		2b		X		C	C		C		C			C	C			C	C					
Current unbalance		2b		X		C	C	C	C	C	C			C	C		C		C					
Grid Impedance variations		1b		X		C	C	C	C	C	C	C		C	C		C		C			C*	C*	C
Island operation		1b		X		C	C	C	C	C	C	C		C	C		C	C	C			C*	C*	C
RoCoF – real df/dt – capability		1b		X		C	C	C	C		C	C	C	C	C		C	C	C			C*	C*	C
Phase jump		1b		X		C	C	C	C		C	C	C	C	C		C	C	C			C*	C*	C
Grid forming		1a																						

P: Perfomance test C: capability test F: Functional test

(1,2,3,4): refers to turbine type I, II, III and IV * Can be emulated

The control functions are listed as functionality, instead of the physical HW (Turbine controller etc.), as the physical HW implementation of these controller functions can variate from WT type and manufacture.

Annex C
(informative)

Replacement of components

C.1 Introduction

The aim of the following chapter is to describe a standardized workflow to avoid complete repeating of a grid compliance measurement on a wind turbine in field or on a test bench by changing individual components or releasing new software versions.

C.2 Definition of components

This process is considering both changes to hardware or software of the turbine:

1. Adaption or improvement of software

   The software changes includes that one of the turbine controllers, the converter, safety system or other software of components are updated. The assumption is that a prototype of a product family has been tested with appropriate software and there is a certificate or equivalent attestation that the grid compliance is fulfilled.

2. Adaption or improvement of hardware

   The hardware includes all relevant hardware components of a turbine. The assumption is that a prototype was tested with a defined set of components in the field or on test bench. Either at the same time or later, it is decided that this type of wind turbine will be sold with other components, for example, from another manufacturer. Also considering parts of a component being adjusted to increase performance. These component adjustments or manufacturer change should not result in the automatic loss of measurement results or certificates. Rather, an analysis should conclude if this adaptation affects the grid compliance properties.

C.3 Workflow replacement of component

The following Figure 43 shows a standardized workflow for replacement of a hard- and software component. A detailed description about the workflow and the definition of each box is stated below.

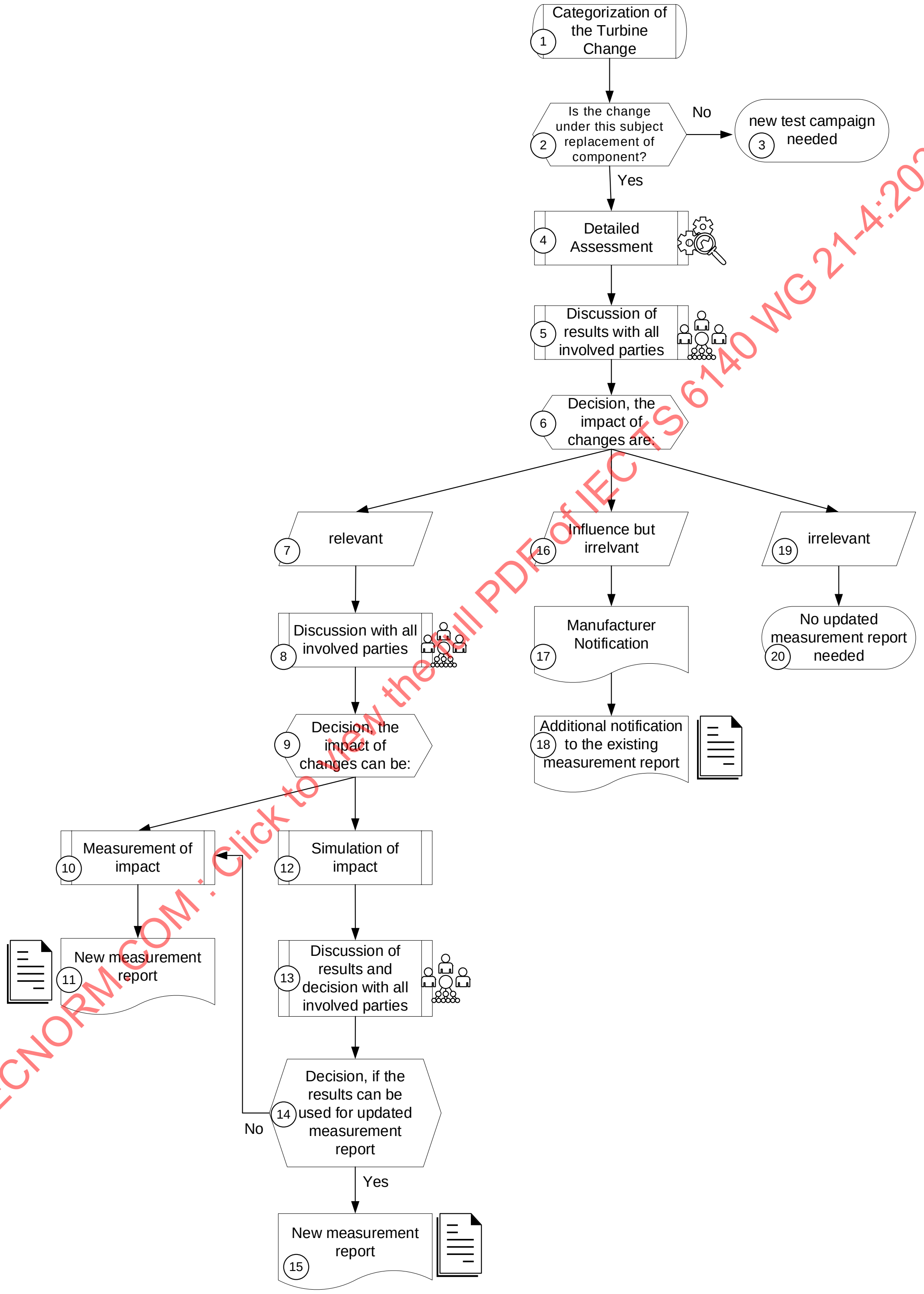


Figure 43 - Flowchart of the procedure to handle a hardware or software update

1) Categorization of the Turbine Change

A software or hardware component is replaced by the manufacture and the process of reassessment starts. It has to be checked, if the change is a subject of the described process of replacement of components. The workflow can be used, if the changed component is listed in Figure 4 and the change is done at the same product family as the tested prototype (see IEC 61400-21-1: 2019, Annex F).

2) Is the change under this subject replacement of component?

If the change fulfills the criteria in Box 1, the described process of reassessment in Box 4 can be follow. Otherwise, the change does not fulfill the criteria in Box 1 and a new test campaign is needed, as describes in Box 3.

3) New test campaign needed

A new measurement according to Chapter 7.1 or IEC 61400-21-1 must be done.

4) Detailed assessment

A first assessment of the influence on the electrical characteristics is done by the manufacture. The results of the assessment process shall be summarized in a report. The report includes the following information:

- Description/ Specification of changed parameters or hardware component
- Reason for the change of component
- Description of the affected properties and functions of the turbine
- Which tests according to Table XXX (Annex B) consider the component?
- Results of the evaluation

5) Discussion of results with all involved parties

The evaluation report is discussed with all involved parties and a decision is made on the impact of changes. There are three categories:

- Relevant: Change has an influence on the electrical characteristics
- Influence but irrelevant: Change have an insignificant impact on the electrical characteristics of the wind turbine, which can be neglected
- Irrelevant: Change has no influence on the electrical characteristics of the wind turbine

6) Decision

Depending on the categorization in Box 5, three different paths of actions are defined:

- Relevant: Box 7 to Box 18
- Influence but irrelevant: Box 19 to Box 22
- Irrelevant: Box 23 to Box 24

7) <u>Path: relevant</u>

If the changes are relevant for the electrical characteristics, then two options for analysis are available:

- Measurement of impact (Box 10)
- Simulation of impact (Box 14)

The classification of impact and definition of test cases is based on a discussion with all involved parties (Box 8 and Box 9). Table 22 and Table 23 in Annex B can serve as the basis for discussion.

Box 10.Measurement of impact

The measurement can be divided in two categories:

a. A remeasurement of the affected grid compliance characteristics at the upgraded complete wind turbine in the field according to IEC 61400-21-1 or test bench according to Chapter 7.1.
b. A remeasurement of the affected grid compliance characteristics on the adjusted or replaced component on a test bench

For a remeasurement at the upgrades complete turbine in field see IEC 61400-21-1 and on test bench see Chapter 7.1. A test procedure for a remeasurement on the adjusted or replaced component on a test bench is described in C.4.

Box 11.New measurement report

The results of measurement have to be summarized in a new measurement report. The new measurement report also includes a comparison between the test results with the reference component and the changed component.

Box 12.Simulation

The grid scenarios for simulation are defined according to the test cases. The simulation is based on a validated model of the DUT and an adapted model of the DUT. The validated model must be adapted according to the changes. The simulation must be done with the validated model and the adapted model. The results of the simulation with the validated model represent the reference. A comparison must be done with the simulation results.

Box 13.Discussion of results decision with all involved parties

The simulation results are discussed with all involved parties and a decision is made on the influence of changes on the electrical properties, either an additional Notification for the measurement report is made or a new measurement (Box 10) can be carried out.

Box 14.decision with all involved parties

A decision is made on the influence of changes on the electrical properties, either an additional Notification for the measurement report is made or a new measurement (Box 10) can be carried out.

Box 15.New measurement report

The simulation results are included in the existing measurement report as an additional notification.

Box 16. <u>Path: Influence but irrelevant</u>

If the changes have an influence in the electrical characteristics, but modifications are irrelevant for the grid characteristics, the follow path can be used.

Box 17. Manufacturer notifications

The manufacturer prepares a manufacturer notification based on the detailed assessment report (Box 4).

Box 18. Additional notification to existing report

The manufacture notification is included in the existing measurement report as an additional notification.

Box 19. <u>Path: Irrelevant</u>

If the changes are irrelevant, no further action is needed.

Box 20. No updated measurement report needed

The existing measurement report is not updated and can be used for other processes.

Note: If a certification procedure exists, the updated measurement report will be passed to the certification body to update the certificate.

C.4 Test & measurement procedure

When measuring a complete turbine in the field, you can simplify the in- and output as illustrated in Figure 44. The turbine is integrated in a specific environment, such as:

- the variable primary energy input
- the electrical network which consuming the electrical energy output
- the parameters that determine the mode of operation of the DUT in relation to the operating point.
- Eventually reference values like P, Q, U, cos phi, etc.

Generally, the physical quantities at the input and output of the DUT are measured as shown in (s. Figure 44.

The network changes or network disturbances shown in the illustration below can, for example, represent voltage dips or even network preloads. The measurement results are either used for project-related analyses or evaluated regarding grid codes.

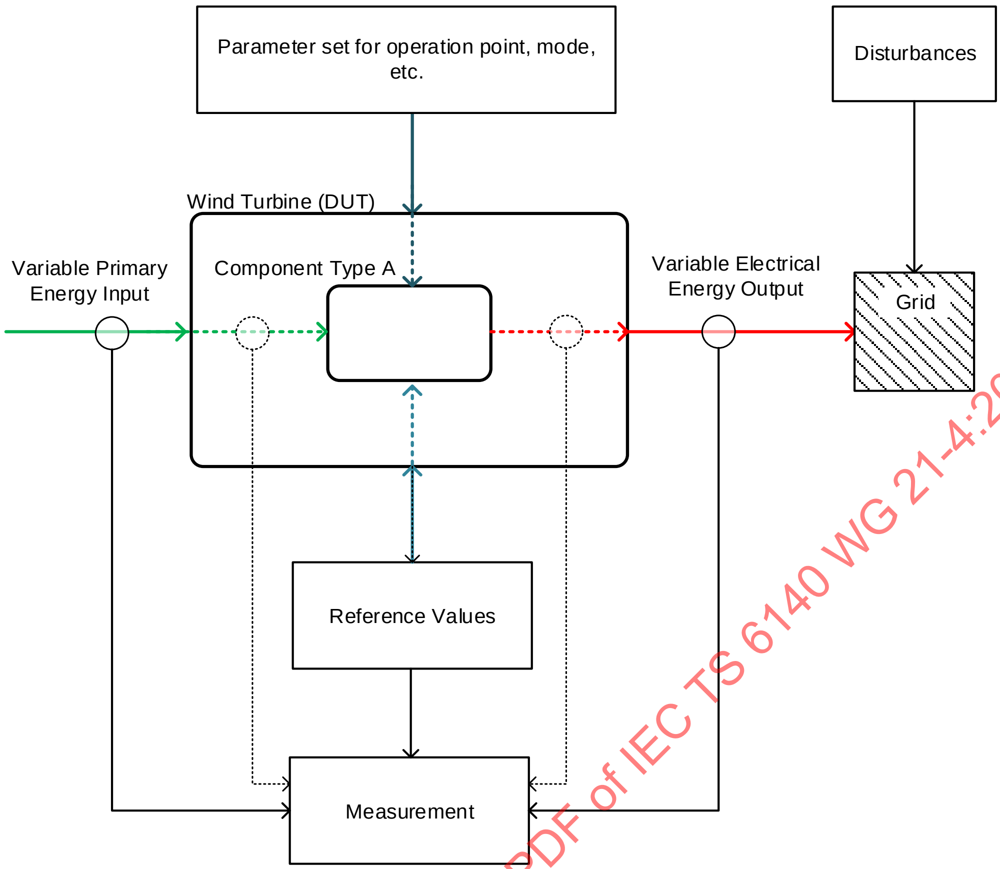


Figure 44 - Illustration of a set-up on a test field, when testing a complete wind turbine with the in- and outputs, the parameter, references, measurements, the grid and disturbances including a certain component type A.

First step:

The first step to show that a component change shows the same electrical behavior is, to make sure that at least the electrical environment is the same within certain limits compare to the related basis measurement (e.g. a field test).

More specifically, should the DUT now represent a single component to be tested on a test bench, the environmental conditions should be adapted to the test in the field.

If a test on a wind turbine in the field is performed first, the boundary conditions as well as the measurement results are present (solid lines). If, at the time of the field measurements, the inputs and outputs as well as, if different, the border conditions (dashed line) are also indicated, this can later be used to measure a modified component on, for example, a test bench. As described, it is always important to adapt the boundary conditions as well as possible to the field measurements.

Second step:

The second is to test the component type A again with some reduced test cases on a test rig and measure the same in and outputs as done during the field tests (s. Figure 45)